WATER INFORMATION BULLETIN NO. 12

ARTIFICIAL RECHARGE TO THE SNAKE PLAIN AQUIFER IN IDAHO; AN EVALUATION OF POTENTIAL AND EFFECT

By

R. F. Norvitch, C. A. Thomas, and R. J. Madison

United States Geological Survey

Prepared by the United States Geological Survey

in Cooperation with

Idaho Department of Reclamation

Published by

Idaho Department of Reclamation

R. Keith Higginson

State Reclamation Engineer

August 1969

Copy 2

CONTENTS

10-29-0101

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd.)

TABLES

ARTIFICIAL RECHARGE TO THE SNAKE PLAIN AQUIFER IN IDAHO
AN EVALUATION OF POTENTIAL AND EFFECT

By R. F. Norvitch, C. A. Thomas, and R. J. Madison

ABSTRACT

The major factors involved in using surplus water for artificial recharge of the Snake Plain aquifer in southern and southeastern Idaho are the availability of water, the probable effects of water mixing on ground-water quality and physical aquifer properties, and the effects of artificial recharge on ground-water levels and aquifer discharge. About 4,000,000 acre-feet of water is recharged to the aquifer annually as a result of irrigation from surface-water sources while 1,100,000 acre-feet of the ground water pumped returns to the aquifer.

Milner Dam is the last major gravity diversion point on the Snake River. Any excess water flowing past this point might have been diverted upstream for artificial recharge. A graph showing the recurrence interval of annual mean discharge of Snake River at Milner indicates that an average flow of about 1.3 million acre-feet or more occurs at a rate of once every 2 years. This indicates a 50 percent probability that the same discharge may be equalled or exceeded in any 1 year. The high degree of regulation of the river above Milner required complete adjustment of the streamflow data obtained at the Milner gage to derive the curve on the graph.

A generalized appraisal of the chemical quality of the surface and ground water in the Snake River Plain shows that there probably will be no chemical-quality problems involved in large-scale recharge.

A transient state, electric-analog model of the Snake Plain aquifer was constructed. Model predictions show that by recharging a total of 3.7 million acre-feet of water over a 10-year period at four different places on the Plain, water-level rises of less than 1 to more than 5 feet, measured 21 months after recharge stopped, would occur in the aquifer. If this quantity of water were added at a rate of 62,000 acre-feet per month for 3 continuous months at each place, once every 2 years, and over a 10-year period--3.3 million acre-feet would go into storage in the aquifer and 0.4 million acre-feet would flow out of the springs. These effects would be superimposed upon the existing hydrologic system.

The analog model can predict water-level responses to artificial recharge, or ground-water withdrawal, which are generalized in areal extent and are within a reasonable range of accuracy. But, because of the complexities in the natural hydrologic system and the lack of data for the better definition of the hydrology of the aquifer, deviations from the model predictions must be expected. Future refinement of the model can be made as additional field data are collected.

INTRODUCTION

Since the late 1800's and through the early 1950's, the water table beneath the eastern Snake River Plain rose locally as much as 70 feet as a result of recharge from irrigation. Since about 1954, however, an increased use of ground water together with a decrease in recharge occurring during a number of dry years, has caused local long-term declines in ground-water levels ranging from less than 1 foot to more than 17 feet.

During the past several years, local interest has developed in the possibility and practicality of artificially recharging the ground-water aquifer that underlies the eastern Snake River Plain. In particular, irrigators using ground water are interested in surplus Snake River flows for recharge to fortify their present supplies and to maintain or reduce their pumping lifts. Also, the U. S. Bureau of Reclamation is considering use of surplus water for artificial recharge in some irrigation projects.

Studies by Mundorff (1962) have demonstrated that hundreds of acre-feet of water can be recharged in relatively short periods of time by spreading water onto areas of bare, rough, porous basalt. Unintentional cyclic recharge on a very large scale has resulted from irrigation on the Plain for more than 70 years.

Numerous reports have been written on the geology and hydrology of all or parts of the Snake River Plain in Idaho. Notable among the older ones are a reconnaissance of the geology and water resources of the Plain in southern Idaho by Russell (1902) and a study describing the geology and ground-water conditions of the eastern Plain by Stearns and others (1935). More recently, Mundorff and others (1964) evaluated the quantity of ground water available for irrigation in the Snake River basin in Idaho and included a flow-net analysis of the Snake Plain aquifer. Historic streamflow data, as they relate to water use for irrigation in the Snake River basin, are contained in reports by Hoyt (1935) and Simons (1953). Other streamflow, ground-water level, and water-quality data are published in a series of U. S. Geological Survey Water-Supply Papers.

The eastern Snake River Plain, herein referred to as the Plain, extends roughly 200 miles eastward and northeastward from Bliss to about Ashton (fig. 1). It is a broad undulating surface that is bounded on the north, east, and south by mountain ranges and alluvium-filled intermontane valleys, and on the west by an area of broad, lava-capped plateaus. The rocks underlying the Plain are a series of successive basalt (lava) flows that include interflow beds of pryoclastic and sedimentary materials. This series contains the Snake Plain aquifer, the highest yielding water-bearing sequence of rocks in Idaho. The Snake Plain aquifer extends short distances up some of the peripheral valleys which join the Plain. Its boundary (fig. 1), as drawn arbitrarily at the foot of the surrounding mountains and across the mouths of the intervening valleys, encompasses an area of about 9,600 square miles.

The purpose of this report is to: (1) provide a quantitative estimate of the distribution of irrigation water on the Plain; (2) describe the availability of water for artificial recharge to the Snake Plain aquifer; (3) evaluate the chemical compatibility of the recharge water and the water in the aquifer; and (4) predict, using an analog model, the effects of artificial recharge on water levels in, and discharge from, the aquifer.

Acknowledgments

An appraisal study of this kind is dependent on computations derived from voluminous basic records collected by various governmental agencies and private companies. The bulk of the irrigation data used are in annual compilation reports made by the Idaho State Department of Reclamation and

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE STATE
OF IDAHO DEPARTMENT OF RECLAMATION

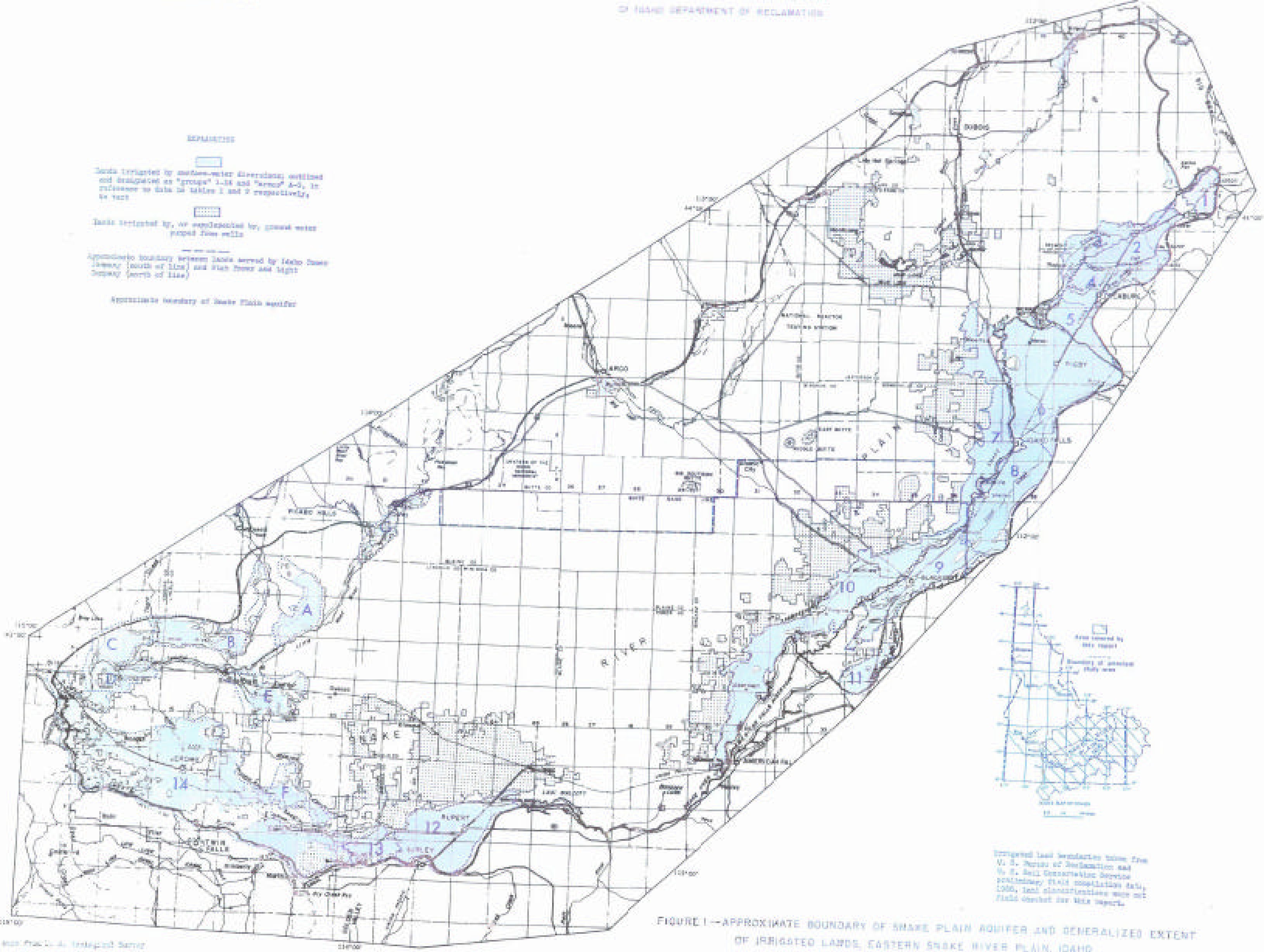

FIGURE 1.—APPROXIMATE BOUNDARY OF SNAKE PLAIN AQUIFER AND GENERALIZED EXTENT OF IRRIGATED LANDS, EASTERN SNAKE RIVER PLAIN, IDAHO

by Water Districts 36, 7-AB and 11-AB. The Northside Pumping Division, Minidoka Project, Rupert, Idaho, and the Snake River Plain Development Office, Boise, Idaho, both of the U. S. Bureau of Reclamation, furnished irrigation records. Records on the distribution of irrigation water on the Fort Hall Indian Reservation were supplied by the Land Operations and Irrigation Department, Fort Hall Agency of the U. S. Bureau of Indian Affairs, Fort Hall, Idaho. The Big Wood Canal Co., Shoshone, Idaho, supplied reports on distribution of irrigation water to lands in the northwestern part of the study area. The Idaho Power Company, Boise, Idaho and the Rexburg, Idaho Branch of the Utah Power and Light Company, Salt Lake City, Utah, provided records which were necessary to make estimates of ground-water pumpage for irrigation on the Plain. The authors are sincerely grateful to these organizations.

Special acknowledgment is due Mr. Reid J. Newby, Watermaster of Water Districts 7-AB and 11-AB for time and effort so generously given in explanation of the operation of his district. Thanks also are given to the many individuals and communities who allowed water-level measurements to be made and water samples to be collected in their wells.

The authors are particularly grateful to personnel of the Geological Survey Analog-Model Unit, Pheonix, Arizona, who brought the electric-analog model of the Snake Plain aquifer to its present level of development.

STATUS OF IRRIGATION

History

Except for the relatively recent growth of the nuclear industry at NRTS (National Reactor Testing Station), the economy of the Plain is dependent almost wholly on agriculture. Because the climate is largely semiarid, the success of agriculture is dependent on the availability and management of water for irrigation.

Irrigation began on the Plain in the latter half of the nineteenth century. The Carey Act of 1894 and the Federal Reclamation Act of 1902 provided the primary incentives and the means for a rapid growth of irrigation in the early 1900's.

Most of the easily accessible, arable land on the Plain was developed by the mid-1920's. The first lands irrigated were those to which water could be conveyed by gravity flow in canals adjacent to the streams. Since the mid-1920's and continuing until about the late 1940's, a tapering off occurred in the growth of irrigated acreage. In the late 1940's, a resurgence in land development was brought about by the use of ground water for irrigation. By late 1965, an estimated 43 percent of all irrigated land within the Plain was either wholly or supplementally supplied by ground water pumped from wells. The percentage continues to rise because arable lands that were formerly considered economically inaccessible for irrigation can now be supplied with water from deep wells.

Present Irrigation

As of the end of the 1965 irrigation season, an estimated 1,510,000 acres were irrigated within the area shown on figure 1--910,000 acres by surface-water diversions and 600,000 acres by ground-water pumping. About 6 percent (52,000 acres) of the area irrigated by surface water is supplemented with ground water.

The generalized areal extent of the irrigated lands is shown on figure 1. Classification of these lands as to source of irrigation water was done by gleaning information from county compilation maps, from previously compiled irrigated-area maps, and from limited field observations.

The boundaries of irrigated lands drawn in this report are approximate, and the water distributions given are estimates. They were made solely for use in this study of the Snake Plain hydrologic system. They do not preclude the need for a detailed quantitative study of water use on the Plain.

Surface Water

An average of about 6,600,000 acre-feet of surface water is delivered annually to the heads of the main canals which distribute water to the lands classified as "irrigated by surface-water diversion" on figure 1. (Note 3 percent of total lands excepted below.) Of this total, about 4,000,000 acre-feet, or about 60 percent, seeps into the ground and recharges the Snake Plain aquifer.

In order to summarize herein the distribution of this tremendous volume of irrigation water, the lands classified as "irrigated by surface-water diversion" on figure 1 were subdivided into "groups" (designated by numbers 1-14) and "areas" (designated by letters A-G). Lands along the northern boundary of the Plain that were not included in either "groups" or "areas" account for less than 3 percent of the total lands irrigated by surface-water diversion. No attempt was made to describe their distribution.

An analysis of the distribution of irrigation water was made for each parcel of land subdivided as above. The total quantity of water distributed to each subdivision was equated to that part of the water that leaves plus that part of the water that remains in a subdivision. That is, the sum of the water that leaves, including (1) consumptive irrigation requirements (Jensen and Criddle, 1962), (2) evaporation from water surfaces in the main canals, and (3) waste water returned to the streams was combined with the sum of the water that remains, including (4) deep percolation losses through canal beds and (5) deep percolation from farm fields. The two combined sums then were made to equal the total quantity of water distributed. Estimates of water volumes were made for the first four items above; the fifth item, then was computed to be the difference between the total of the first four items and the total quantity of water distributed to the subdivision. No direct means were available to obtain values for items 2, 3, and 4 above; therefore, estimates of 5 percent, 3 to 20 percent, and 10 to 30 percent, respectively, were used. These estimates, based largely on fragmentary evidence and on judgment, were varied in different parts of the Plain.

Data used in table 1 were derived from the annual records compiled by Water District 36. Because little change has occurred in the distribution system since activation of Palisades Reservoir in 1956, the average annual (1956-65) figures shown in table 1 probably represent the status of irrigation to date. In table 1, column 4 is the average annual total diversions at the head of the main canals in each group and was obtained from records of flow measurements. Column 5 was obtained by dividing column 4 by the total irrigated acreage in each group thus column 4 divided by column 5 gives the average number of acres irrigated annually in each group. Column 6 was derived by adjusting column 5 for estimates of deep percolation through canal beds, evaporation from the canal distribution system, and waste water return to streams, and thus gives an estimate of the volume of water per acre spread on the crops. Column 7 is column 6 minus the consumptive irrigation requirement and plus the percolation losses through canal beds. It shows, for each canal group, the total amount of water per irrigated acre that recharges the Snake Plain aquifer, and in some areas exceeds the value for water spread because canal losses are so high.

Data used in table 2 were derived from reports compiled by the Big Wood Canal Co., and from records collected by Water Districts 7-AB and 11-AB. The distribution breakdown in table 2 begins with total diversions at farm headgates (column 4) rather than at the head of main canals, as is done in table 1.

Therefore, column 6 shows the estimated deep percolation only from crop lands; it does not include the deep percolation from the main canals. The average annual total diversions at the head of the distribution systems to the lettered "areas" A-F are estimated to be 260,000 acre-feet, or 7.3 acre-feet per acre from Magic Reservoir; and 422,000 acre-feet or 7.1 acre-feet per acre, through the Milner-Gooding Canal.

Data are included in both tables 1 (column 8) and 2 (column 7) so that diversions for 1961, the lowest year in the decade for water availability, can be compared with the average annual diversions. Comparison shows that the distribution of water to lands in the lettered "areas" is considerably less during a low-water year. Although not affected as greatly, lands in the numbered "groups" lost from 0.0 to 1.4 acre-feet per acre in water distributed to the crops and from 0.1 to 1.7 acre-feet per acre in water recharged to the Snake Plain aquifer. Although the crops received enough water for growth, there was a significant reduction in recharge to the aquifer.

Ground Water

In 1965, an estimated 2,100,000 acre-feet of water was pumped from wells to irrigate the lands classified as "irrigated by, or supplemented by, ground water" shown on figure 1. This amounts to about 3.3 acre-feet per acre per irrigation season for lands irrigated solely by ground water, and about 1.8 acre-feet per acre for lands supplemented by ground water. Of the total, about 1,100,000 acre-feet, or 52 percent, of the pumped water re-entered the ground as return flow to the Snake Plain aquifer. The ground-water pumpage estimates were derived from data obtained from IPCo (Idaho Power Co.) and UPLCo (Utah Power and Light Co.). The line separating the territories served by each power company is shown on figure 1. Figures 2 and 3 are graphs showing the estimated gross and net pumpage (gross pumpage minus consumptive

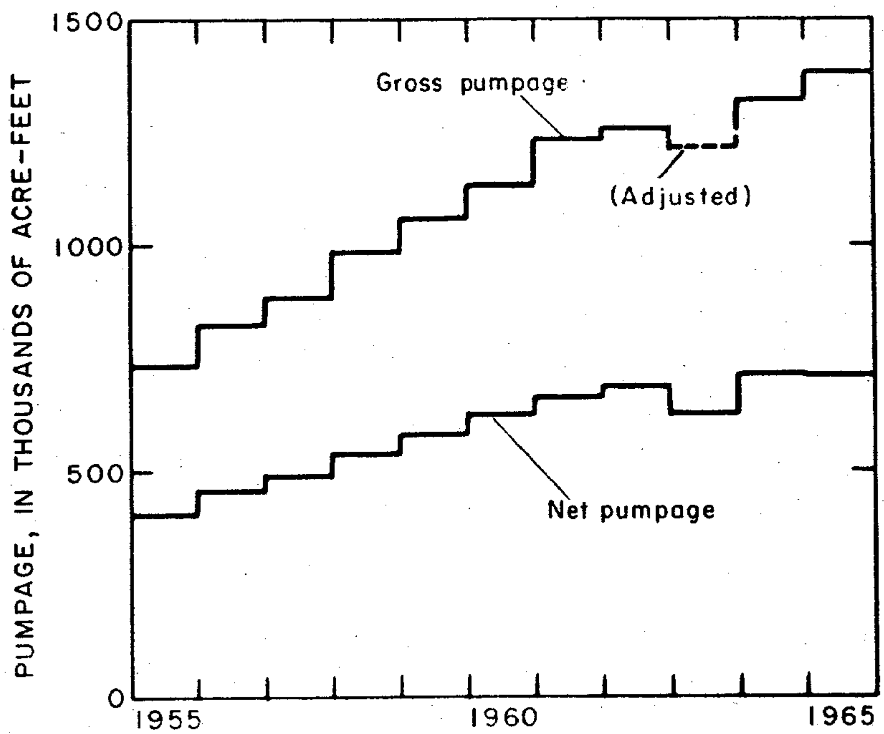

FIGURE 2.--Estimated annual volumes of ground water pumped for irrigation on lands served by Idaho Power Company.

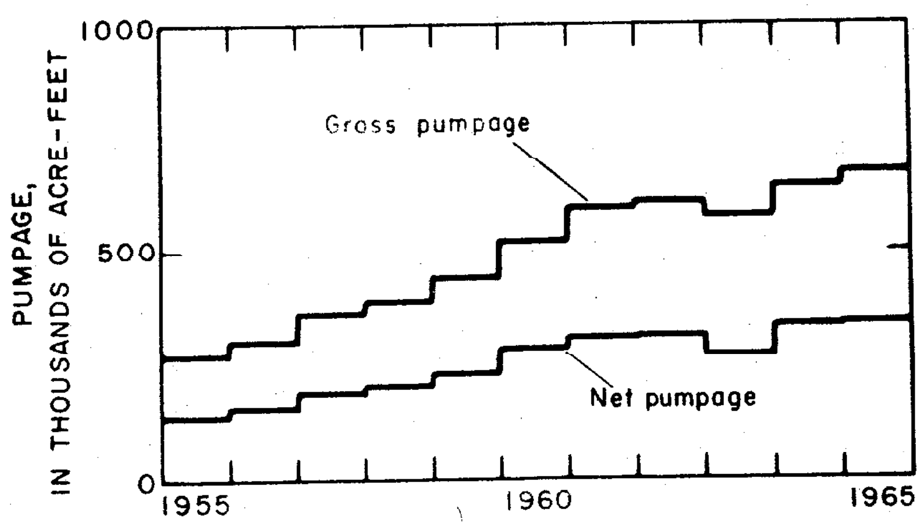

FIGURE 3.--Estimated annual volumes of ground water pumped for irrigation on lands served by Utah Power and Light Company.

irrigation requirements) in the period 1955-65 for lands served by the IPCo and the UPLCo, respectively.

Estimated gross pumpage in the IPCo territory was computed by multiplying the total acres annually irrigated, either wholly with ground water or supplemented with ground water, by 3.3 and 1.8 acre-feet per acre, respectively. The total annual acreage was obtained through a cumulative compilation made from listings of the number of (new) acres brought under irrigation each year within the individual IPCo districts.

Estimated gross pumpage in the UPLCo territory was computed by applying the total annual KWH (kilowatt-hours) used to the following formula:

$$V = 0.98 \frac{Eo}{h} \ KWH$$

Where V = pumpage in acre-feet

h = total head (pumping lift and discharge head)

Eo = overall wire to water efficiency

KWH = kilowatt-hours

The annual KWH were tabulated for subdivisions within the territory. An average h value was computed for each subdivision and an estimated Eo was used to apply the formula.

Approximations of net pumpage for both territories were made by using the average annual percentage of pumped ground water that was consumed in a control area, the Minidoka Northside Project, U. S. Bureau of Reclamation. This percentage, adjusted to varying conditions in the other areas of ground-water irrigation on the different parts of the Plain, then was applied to the previously computed gross pumpage to obtain net pumpage. Because of above-normal rainfall during the 1963 irrigation season, gross and net pumpage, as shown on figures 2 and 3, are down despite an increase in ground-water irrigated acreage.

Table 1. Distribution of surface water applied for irrigation on lands adjacent to Henrys Fork and the Snake River.

(1) Group	(2) Canal	(3) Major stream source 1/	(4) Average annual 2/ total diversions at head of main canals (acre feet)	(5) Average annual 2/ total distribution (acre feet/acre)	(6) Estimated average annual distribution to crops (acre feet/acre)	(7) Estimated average annual deep percolation from all lands 3/ (acre feet/acre)	(8) 1961 distribution Total diversions (acre feet)	(8) 1961 distribution Distribution to lands (acre feet/acre)	(8) 1961 distribution Estimated distribution to crops (acre feet/acre)	(8) 1961 distribution Estimated deep percolation (acre feet/acre)
1	Farmers Own 4/ Marysville 4/	FR FR	33,400	2.6	1.8	1.2	27,300	2.1	1.4	0.7
2	Silkey McBee Bell Stewart Pioneer Good Luck Wilford Salem Union Farmers Friend Twin Groves Crosscut Roxana North Salem Pincock-Byington Consolidated 5/ Farmers	FR FR FR TR TR TR TR HF HF HF HF NFTR NFTR NFTR HF	198,700	10.1	6.5	6.6	169,900	8.7	5.6	5.6
3	St. Anthony Union Last Chance Dewey Independent St. Anthony Union Feeder Egin	HF HF HF HF HF HF	348,300	12.3	7.0	8.1	317,400	11.2	6.3	7.2
4	Curr Chester Fall River Enterprise Almy Teton Irrigation Siddoway Saurey Sommers Island Ward Teton Island Feeder Gardner Pincock-Garner Rexburg Irrigation City of Rexburg Woodmansee-Johnson McCormick-Rowe Eames-Thompson Consolidated Farmers 5/	FR FR FR FR FR TR TR NFTR NFTR NFTR NFTR NFTR SFTR SFTR SFTR SFTR SFTR HF	394,500	8.7	4.9	5.0	343,600	7.6	4.3	4.3
5	Nelson-Corey Hill-Pettinger Texas Feeder Reid Lenrot Sunnydell	SR SR SR SR SR SR	200,100	8.8	5.0	5.2	171,300	7.7	4.4	4.3
	Cheney Harrison Steele Ross and Rand Butler Island Mattson-Craig Nelson Arnsberger	SR SR SR SR SR SR SR SR								

	Enterprise Farmers Friend Progressive Long Island and West LaBelle Rigby Island Dilts East LaBelle Clark and Edwards Burgess Kite and Nord Lowder-Jennings Boomer-Rudy Bramwell Ellis White North Rigby Parks and Lewisville	SR SR SR SR SR SR SR SR SR SR SR SR SR SR SR SR SR SR	1,206,200	9.6	5.8	5.6	1,131,400	9.0	5.5	5.2
7	Bear Island and Smith Great Western Group Porter New Sweden Martin West Side Mutual Kennedy Osgooc Butte and Market Lake Woodville	SR SR SR SR SR SR	357,900	5.9	3.4	3.7	303,300	5.4	3.1	3.2
8	Snake River Valley Idaho		443,000	7.7	5.0	5.3	441,000	7.7	5.0	5.2
9	Nielsen-Hanser Corbett Slough Blackfoot Reservation 6/	SR SR SR SR	221,300	6.6	4.2	4.6	214,300	6.6	4.2	4.5
10	Parsons Watson Slough Wearyrick Trego Danskin Riverside Aberdeen-Springfield Peoples New Lava Side	SR SR SR SR SR SR SR SR SR	661,300	6.3	4.1	4.1	575,100	5.4	3.5	3.4
11	Fork Hall Main	BR SR SC	109,600	6.1	4.2	4.1	95,100	5.3	3.6	3.4
12	Minidoka	SR	439,400	6.1	4.2	3.3	393,300	5.5	3.7	2.8
13	Minidoka North Side Pump	SR	52,800	3.9	2.6	1.6	54,200	4.5	3.1	2.0
14	North Side PA Lateral	SR SR	1,199,300	7.5	5.5	5.0	890,500	5.6	4.1	3.3

1/ FR, Falls River; TR, Teton River; HF, Henrys Fork; NFTR, North Fork Teton River; SFTR, South Fork Teton River; SR, Snake River; BR, Blackfoot River; SC, Sand Creek

2/ Period 1956-65

3/ Exceeds column 6 in some areas because of high losses from canals

4/ Part of service is outside of report area

5/ Serves land in groups 2 and 4

6/ Part of water goes to Fort Hall Main Canal, group 11

Table 2. Distribution of surface water applied for irrigation on lands in the Hunt tract and adjacent to the Big Wood and Little Wood Rivers.

(1)	(2)	(3)	(4)	(5)	(6)	(7) 1961 distribution		
Area	Tract	Major reservoir source	Average annual 1/ total diversions at farm headgates (acre feet)	Average annual distribution to crops (acre feet/acre)	Estimated average annual deep percolation from crop lands (acre feet/acre)	Total diversions (acre feet)	Distribution to crops (acre feet/acre)	Estimated deep percolation from crop lands (acre feet/acre)
A	Richfield	Magic	69,700	4.2	2.6	20,400	1.4	0
B	North Shoshone	American Falls Magic	76,600	4.1	2.4	40,700	2.5	0.9
C	North Gooding	American Falls	60,700	4.3	2.6	42,600	2.8	1.2
D	South Gooding	American Falls	73,900	4.9	3.1	52,000	3.1	1.4
E	Dietrich	American Falls Magic	46,100	4.7	2.9	19,100	2.2	0.7
F	Hunt	American Falls	32,400 2/	4.6	2.6	22,700	3.0	1.3
G	Carey	Little Wood River Fish Creek	16,000 3/	1.6	0.1	14,600	1.4	0

1/ Period 1956-65

2/ Diversions for 1956-60 are estimated

3/ All estimates

AVAILABILITY OF WATER FOR ARTIFICIAL RECHARGE

The major sources of water for artificial recharge to the Snake Plain aquifer are Snake River (upstream from Milner Dam) and Henrys Fork. Milner Dam marks the last major gravity diversion point on the Snake River. Except for limited releases committed to electric power generation downstream, under the present conditions of irrigation, water flowing past Milner can be considered as surplus to the upper Snake River region.

Other potential sources of water for artificial recharge include the Big Wood River drainage in the northwestern part and Blackfoot and Portneuf Rivers in the eastern part of the Plain. Surplus flood water is available in most years from the Big Wood River drainage (Mundorff, 1962, p. 12). Diversions for recharge from the Blackfoot and Portneuf Rivers would reduce water now available for storage downstream, and probably would necessitate some sort of a water exchange plan.

Only the major sources of water are evaluated here. Figure 4 shows the location of these water sources and other pertinent water-resource data. As implied above, the key point in the system is Milner Dam. Any excess streamflow past that point might have been diverted at some upstream point for artificial recharge.

A graph showing the theoretical recurrence interval of annual mean discharge, based on 55 years of record of the Snake River at Milner, is shown in figure 5. The high degree of regulation of the river above Milner required complete adjustment of the streamflow data obtained at the Milner gage (fig. 4) to derive the curve on the graph. Unadjusted gaged flow at Milner, under the regulated conditions, ranged from 2 cfs (cubic feet per second) to as much as 40,000 cfs. The compilation for the graph was based on monthly discharge records that were adjusted for storage and diversion to convert them to the 1956-65 conditions of river control. In making the conversion, release of water past Milner was assumed only when upstream storage was full and estimated diversion needs were met. The lower, initial part of the curve in figure 5 is flat because, under the assumed conditions, in 15 of the 55 years of record, virtually no water would have spilled past Milner. In all 55 years of record, no water would have spilled past Milner in August, September, October, or November. In August and September, diversions for irrigation always exceeded inflow to the reservoirs; that is, more water was going out of storage than was coming into storage. In October and November space was always available in upstream reservoirs because of withdrawals from storage made during the previous irrigation season. Release of water would have been necessary in 180 months during the 55-year period and would have occurred most often in April, followed by May, March, June, February, January, December and July.

The graph shows the statistical frequency of streamflow past Milner and, therefore, the probable availability of water for artificial recharge. For example, as shown on the graph, an annual mean discharge of about 1,750 cfs (about 1.3 million acre-feet) or more occurs at a rate of once every 2 years, indicating a 50 percent probability that the same discharge may be equalled or exceeded in any 1 year. It should be recognized, when using the graph, that the predicted probability of flows does not in any way indicate the time of occurrence but only the probability of recurrence in years.

In actual practice, the release of water past Milner occurs in patterns different from the theoretical monthly determinations stated above. When it is anticipated that streamflow will more than fill the remaining reservoir capacity, water is released to create space for the expected inflow. Also storage space is reserved to lessen flood hazards and, during winter months,

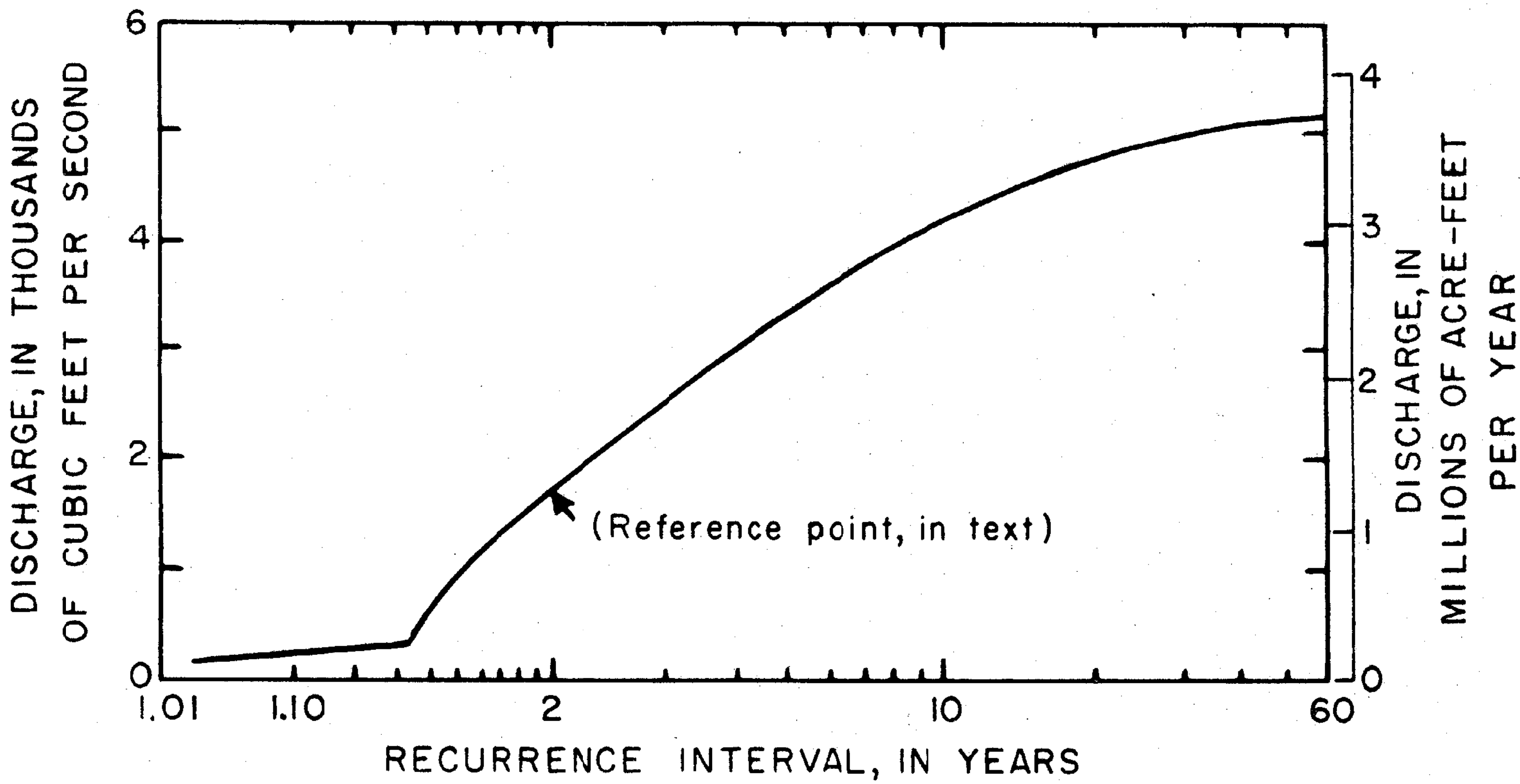

FIGURE 5.--Recurrence interval of annual mean discharge of Snake River at Milner, Idaho.

to prevent damage by ice. Therefore, releases may occur at almost any time of the year, depending on the judgment of the watermaster. The most opportune time to artificially recharge the aquifer would coincide, of course, with the decision to release surplus water at Milner.

The recurrence interval of annual mean discharge in the upper northeastern part of the Plain is shown for Snake River near Heise (fig. 6) and Henrys Fork near Ashton (fig. 7). Discharges used to draw the curves on those graphs were adjusted for storage changes and evaporation from upstream reservoirs; they were not adjusted for diversions.

Average streamflows for the period 1955-65 in the Snake River and in Henrys Fork and its tributaries are shown on figure 4 by width of shaded pattern along the streams. The average flows shown are based on unadjusted discharges measured at gaging sites.

AQUIFER DISCHARGE AND STORAGE

Artificial recharge should increase both discharge and storage of ground water in the Snake Plain aquifer. The relative magnitude of increases in either the rate of natural discharge or the quantity of water in storage will depend on both the location and the volume of water recharged. For example, water applied adjacent to a point of natural discharge would increase discharge promptly, but might have little effect on storage. To maximize storage benefits, recharge sites should be located as far as possible from the river or springs, consistent with storage near or movement to points of planned withdrawal.

Ground-Water Discharge

Most of the natural ground-water discharge from the Snake Plain aquifer occurs from two groups of springs along the Snake River. The easternmost group, extending from the mouth of the Blackfoot River to a short distance below

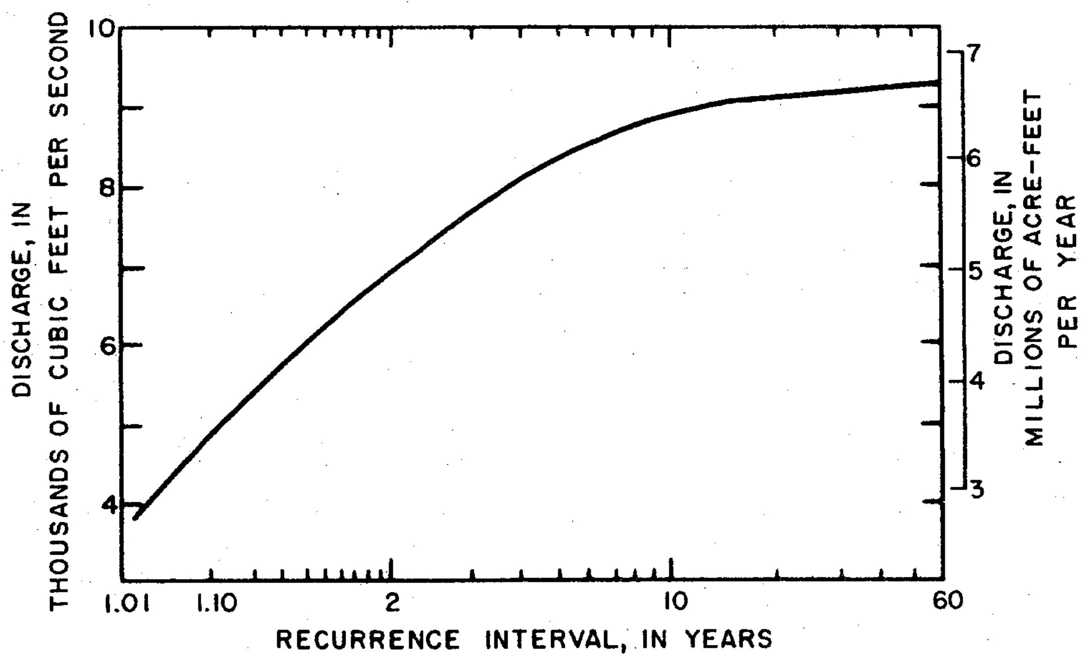

FIGURE 6.--Recurrence interval of annual mean discharge of Snake River near Heise, Idaho.

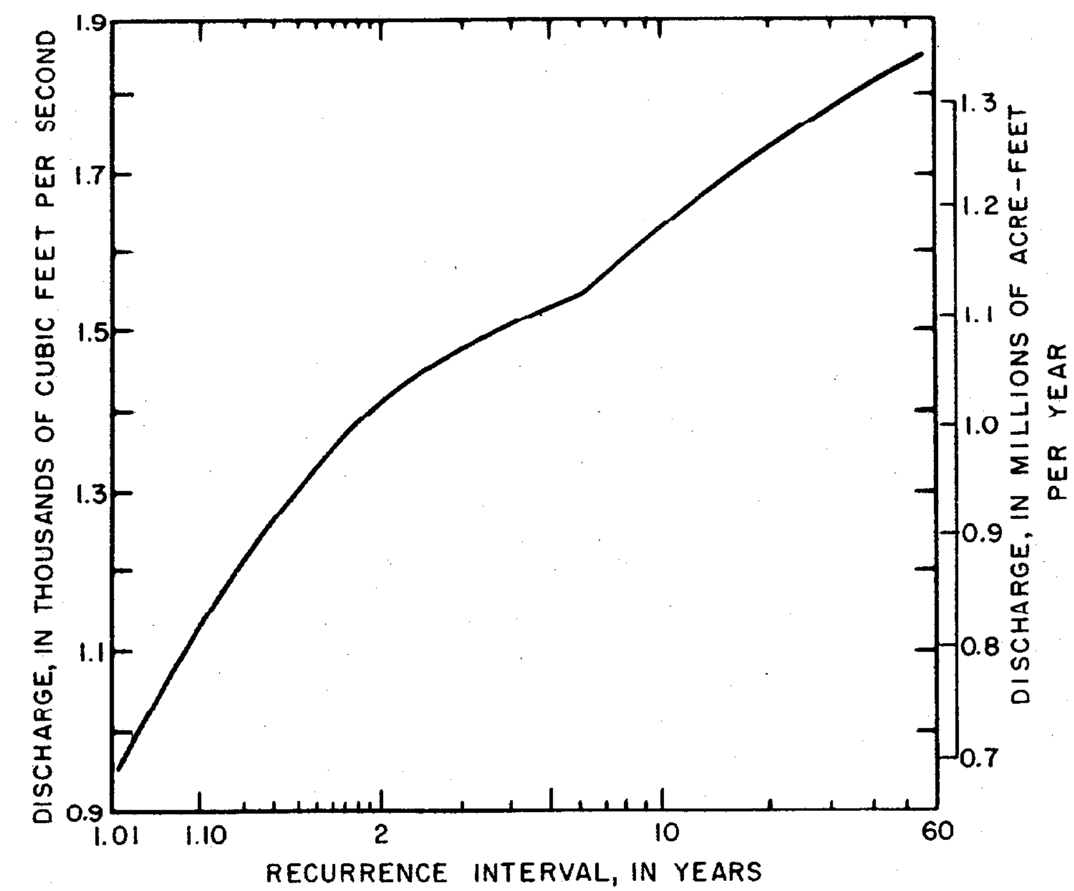

FIGURE 7.--Recurrence interval of annual mean discharge of Henrys Fork near Ashton, Idaho.

American Falls, accounts for about 28 percent of the total discharge, or about 1.8 million acre-feet per year (1954-65 average). The westernmost group, extending from below Milner to King Hill, accounts for about 72 percent of the total discharge, or about 4.7 million acre-feet per year. A third minor group of springs at the eastern end of Lake Walcott and extending a short distance upstream accounts for less than 1 percent of the total discharge.

Most of the water from the easternmost springs discharges into the river above American Falls dam and is captured in that reservoir. Most of the water from the westernmost springs flows into Snake River and out of the eastern Snake River Plain area. Only a small part is used consumptively by irrigation along the bottomlands in the Snake River canyon.

Historical annual mean discharges of the two major spring groups are shown by graphs in figure 8. Total flow in the easternmost springs was determined by deducting the Snake River flow near Blackfoot from the flow at Neeley. Adjustments were made for changes in storage in American Falls Reservoir and for Portneuf River inflow.

Because the spring flow (aquifer discharge) from the westernmost springs issues only from the north side of the river, the total flow of this group was somewhat more difficult to deduce. In addition to subtracting the Snake River flow at Milner from the flow at King Hill, the following volumes of inflow had to be subtracted: 1) natural surface inflow from the north and south sides; 2) inflow from surface wasteways on the north and south sides; and 3) subsurface inflow from the south side. The remainder was considered to be the total discharge from the westernmost springs.

Changes in Ground-Water Storage

A rising water level in an observation well denotes an increase in the quantity of water in storage in an aquifer, whereas, a declining water level

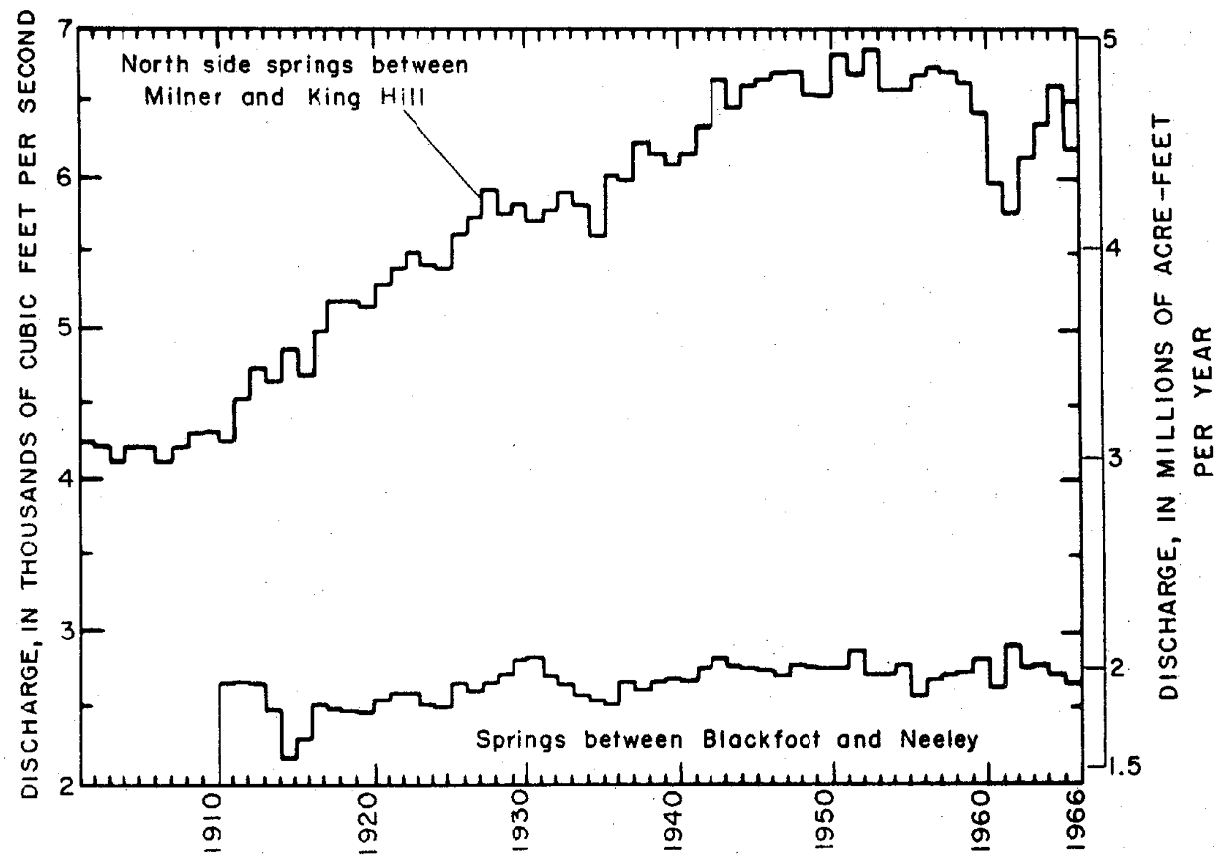

FIGURE 8.--Annual mean discharge from the two major groups of springs draining the Snake Plain aquifer.

denotes a decrease in the quantity of water held in storage. Some reasons for water-level changes in wells in parts of the Snake Plain aquifer were explained by Mundorff and others (1964, p. 163-169).

Hydrographs of water-level changes in 16 selected observation wells in the Snake Plain aquifer illustrate changes in the quantity of ground water held in storage in different parts of the aquifer. (See fig. 4 and table 3.) Inspection of the hydrographs, some of which are not shown in figure 4, reveals that from the early 1950's to the middle 1960's water levels declined about 10 to 20 feet over an area of roughly 2,000 square miles. The general decline (assuming that the few wells for which records are available are representative of the entire aquifer) took place in the southwestern part of the aquifer north of the Snake River, in southeastern Lincoln County, eastern Jerome County, Minidoka County, and the southern panhandle of Blaine County.

The data permit only the crudest estimates of change in ground-water storage, but the decrease appears to be in the neighborhood of 2 million acre-feet in about a 12-year period. Subsequent to 1965, ground-water levels show a slight upward or leveling-out trend in those same counties.

QUALITY OF WATER

In any artificial-recharge project where waters from two different environments are to be mixed, the chemical character of both should be known. This may enable prediction of problems that may arise, and, thereby enable preventive steps to be taken. Figure 9 depicts an overall appraisal of the chemical quality of the surface and ground waters of the eastern Snake River Plain area. The significance of this appraisal is as follows.

Surface Water

In many parts of the Snake River basin, irrigation return flows have increased appreciably the dissolved-solids and the sodium content of the

Table 3.--Observation-well data

Well number	Location	Land surface altitude (Feet above mean sea level)	Depth of well (Feet below land surface)
1	SE¼NE¼ sec. 11, T. 9 N., R. 34 E.	4955*	192
2	SE¼NW¼ sec. 34, T. 7 N., R. 31 E.	4848.8	320
3	NW¼SW¼ sec. 20, T. 7 N., R. 35 E.	4818.2	58
4	NW¼SE¼ sec. 23, T. 7 N., R. 38 E.	4852.4	236
5	SE¼NW¼ sec. 9, T. 5 N., R. 34 E.	4791.3	553
6	SE¼NE¼ sec. 14, T. 3 N., R. 29 E.	4917.9	588
7	NW¼NW¼ sec. 30, T. 1 N., R. 29 E.	5066.9	704
8	SW¼SW¼ sec. 1, T. 1 N., R. 36 E.	4674.0	217
9	NW¼NW¼ sec. 6, T. 4 S., R. 24 E.	4493.4	445
10	NW¼SW¼ sec. 3, T. 4 S., R. 33 E.	4447.9	53
11	SW¼NE¼ sec. 26, T. 5 S., R. 17 E.	3972.6	254
12	NW¼NE¼ sec. 27, T. 5 S., R. 31 E.	4399.8	46
13	SW¼NW¼ sec. 16, T. 8 S., R. 14 E.	3175.3	53
14	NE¼NW¼ sec. 2, T. 8 S., R. 23 E.	4263.6	290
15	NW¼NE¼ sec. 27, T. 8 S., R. 26 E.	4238.5	225
16	NE¼SE¼ sec. 1, T. 9 S., R. 20 E.	4211.3	400

* Altimeter determination

surface waters. However, most of the water is still satisfactory for irrigation of the crops being grown; but, in some areas, treatment would be required before the water could be used for municipal or industrial supply. Some deterioration of water quality should be expected and could become a problem in the future if large increases in irrigation occur.

The headwaters of most tributaries entering the Snake River Plain are of the calcium bicarbonate type and are relatively dilute, containing 160 mg/l (milligrams per liter) dissolved-solids or less. Dissolved-solids content and percent sodium increase markedly downstream, largely as a result of irrigation use. However, waste disposal, mineralized spring flow, and evaporation also contribute to the downstream increase. The dissolved-solids content in some streams entering the Snake River is as much as seven times greater than that in their headwaters (Laird, 1964, p. 1).

Waters in the major tributaries entering the Snake River from the north are of the calcium-magnesium bicarbonate type, with small concentrations of sodium, chloride, and sulfate. Their dissolved-solids content ranges from less than 100 to slightly more than 300 mg/l and averages less than 250 mg/l. The sodium percentage normally averages less than 25.

Waters in tributaries entering the Snake River from the south are commonly more highly mineralized than the northern waters and have larger percentages of sodium, chloride, and sulfate. The higher dissolved-solids content is attributed to a combination of several factors, including more arid conditions, more extensive irrigation, relatively higher salt content in the valley-fill sediments, and contributory flow from mineralized spring discharge.

The main stem of the Snake River shows downstream changes in chemical quality which reflect both man's use and the effects of waters of different natural quality entering the stream. Samples collected during a low-flow period in 1965, in the reach from the Idaho-Wyoming border to Buhl, Idaho, showed a progressive increase in both SAR (sodium-adsorption ratio) and dissolved-solids content (McConnell, 1967). The SAR increased from 0.2 to 1.5 and dissolved solids increased from about 175 to more than 400 mg/l. Below Buhl, the dissolved-solids content decreased to 340 mg/l because of inflow of less mineralized spring water.

In parts of the Henrys Fork basin, unusually high concentrations of fluoride occur. Laird (1964, p. 14) reported concentrations of more than 4 mg/1 in places. Fluoride content in Henrys Fork, from Island Park Reservoir to its mouth, ranged from 1.4 to 1.8 mg/1. The higher fluoride concentrations occur in streams draining the volcanic rocks in the northern and eastern parts of the basin.

Little is known of the sediment-transport characteristics of the streams on the Snake River Plain. Rainwater (1962) delineated the area into zones of average annual discharge-weighted mean concentrations of suspended sediment. Those zones covered three ranges: less than 270 mg/1, 270-1900 mg/1, and 1900-5600 mg/1. The zones of highest concentration were in the southwest corner of the study area and in a wide band north of the Snake River and west of Henrys Fork, extending from near Ashton to King Hill. The zones of lowest concentration covered the upper reaches of the tributaries from the north and northeast and a narrow strip along the Snake River upstream from Burley.

Measurements of suspended-sediment concentration were made by the U. S. Geological Survey and the U. S. Bureau of Reclamation at sites (fig. 9) on several streams on the Snake River Plain during the period 1960-66. The data obtained are from spot measurements and are summarized in the following table:

Station Number	Station	Days Sampled	Observed concentration (mg/1)	
			Maximum	Minimum
13-375	Snake River near Heise	10	63	8
13-505	Henrys Fork at St. Anthony	26	80	5
13-550	Teton River near St. Anthony	27	369	25
13-600	Snake River near Shelley	9	165	25
13-695	Snake River near Blackfoot	6	151	34
13-755	Portneuf River at Pocatello	6	2600	62
13-770	Snake River at Neeley	1	22	-
13-1170	Birch Creek near Reno	12	32	5

Although these data are insufficient to give conclusive results, they do indicate that the concentration shown on the map by Rainwater (1962) may be somewhat high in places.

Ground Water

The chemical character of the ground water in the Snake Plain aquifer is determined primarily by the chemical character of the water recharging the aquifer. Most water entering the Plain on the north and recharging the aquifer (fig. 9) has a dissolved-solids content averaging less than about 250 mg/l. Ground water in the down-gradient part of the Plain and distant from irrigated areas also contains less than 250 mg/l dissolved solids, indicating that natural increases from dissolving of minerals in the basalt aquifer are slight.

The greatest change in the chemical quality of the ground water in the aquifer occurs probably as a result of recharge from irrigation water. The isopleth lines shown in figure 9 enclose areas where most of the ground waters sampled contain more than 250 mg/l dissolved solids. Those areas coincide closely with areas of irrigation.

As irrigation water percolates through the soils, leaching and ion-exchange reactions take place. When the water reaches the aquifer, it contains a larger percentage of chloride, sulfate, and sodium and a smaller percentage of bicarbonate than originally. Figure 10 shows diagrams which compare the different waters. In the irrigated areas, the sodium content of ground waters ranges from less than 10 to more than 60 percent of the dissolved cations and sulfate-plus-chloride content ranges from 10 to 70 percent of the dissolved anions. Where the ground water is not affected by recharge from irrigation, the percentage of sodium, and of sulfate plus chloride is usually much less.

The NRTS discharges waste water underground in the area east of Arco, Idaho, but the gross chemical effects are small compared with those of

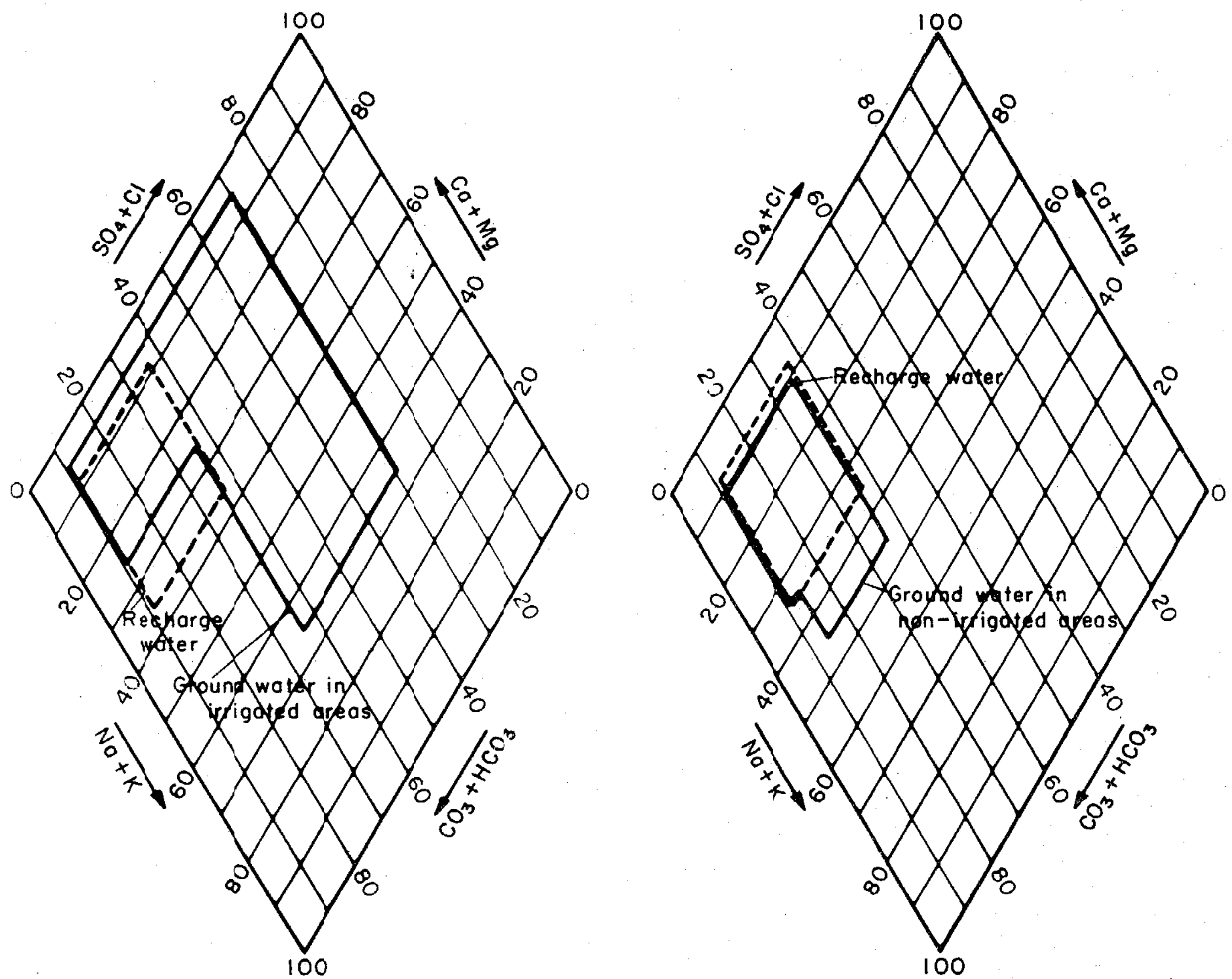

FIGURE 10.--Comparison of quality of recharge water and ground water. Blocks enclose ranges of compositions in percentages.

irrigation. The chemical character of water collected from wells in the NRTS shows considerable variation both laterally and vertically within the aquifer. The dissolved-solids content of ground water sampled in that area ranges from less than 250 to about 1,000 mg/l.

In general, bodies of relatively more saline ground water caused by irrigation or, of much lesser extent, by waste disposal, do not seem to move great distances before dilution occurs either laterally or along the direction of flow within the aquifer. All samples collected from wells in the central part of the Plain have dissolved-solids concentrations of less than 250 mg/l.

Irrigation in the agricultural area between American Falls and Twin Falls apparently has affected materially the underlying ground water. This is indicated by the fact that the mineral content of some springs, such as Devil's Washbowl (SW¼ sec. 34, T. 9 S., R. 18 E.) whose flow is mostly affected by irrigation, is about twice that of some other springs further downstream.

In most areas, the dissolved-solids content of the ground water seems now to be relatively constant with time. However, there probably was a relatively large increase in dissolved solids with the first massive application of irrigation water in the late 1800's and early 1900's but this cannot be proved because pre-irrigation chemical data are lacking.

Ground-water samples were collected periodically in irrigated areas over the 18-year period 1949-66. Chemical analyses of these samples indicate that the quality of water has changed little since 1949. Also, the dissolved-solids content of water from the springs at the lower end of the Plain varies only slightly as is indicated by the small range in specific-conductance values of water from Thousand Springs shown by the graph in figure 11. None of the springs has shown a consistent trend toward either increasing or decreasing dissolved solids with time.

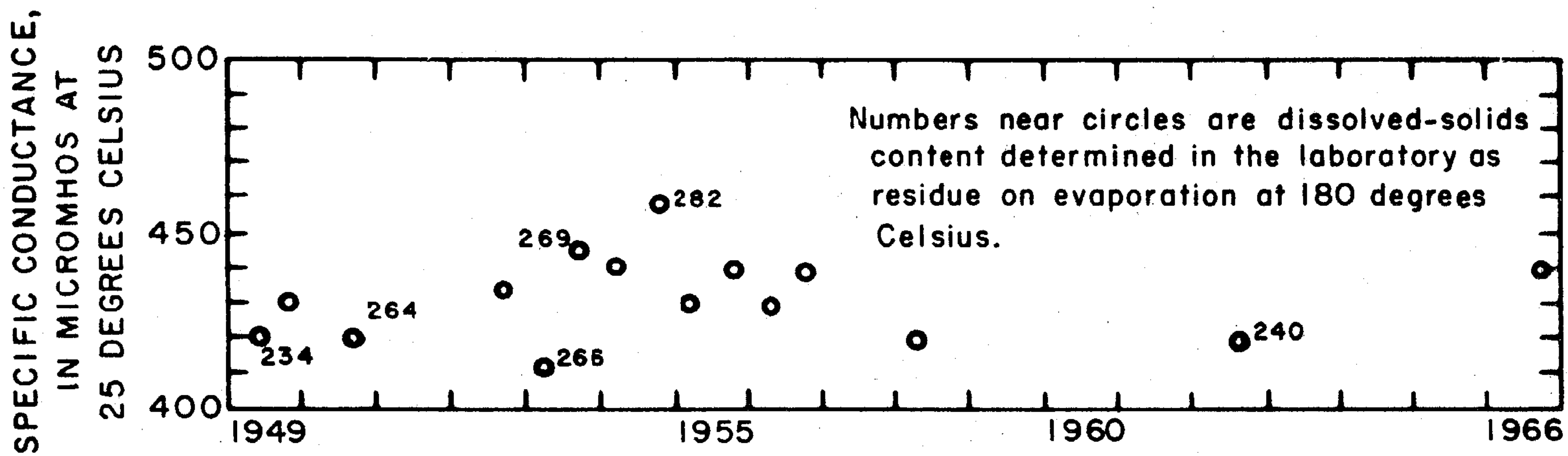

FIGURE 11.--Specific conductance of water at Thousand Springs (sec. 8, T. 8 S., R. 14 E.) near Wendell, Idaho.

The available data are not sufficiently comprehensive to define precisely the effects of irrigation, since its initiation to the present day, on the quality of water in the Snake Plain aquifer system. However, based on comparison of chemical sampling done within the last 20 years, it seems that a very large expansion in irrigated acreage could be effected without increasing salt concentrations in the ground water to a hazardous level. Of 22 water samples collected in 1966 throughout the Snake Plain aquifer, only one (from a well in the NE¼ sec. 33, T. 9 S., R. 22 E., fig. 9) had properties that may constitute a salinity hazard to crops that do not have a good salt tolerance and that are grown on soils with restricted drainage.

Water Quality and Artificial Recharge

Predictions based on the reactions that may occur when two different waters are mixed in an aquifer could cover practically the entire scope of soil-water chemistry. Monitoring systems set up at actual artificial-recharge sites are perhaps the only positive means by which changes might be determined. Establishment of such monitoring systems and the results obtained through their use, are discussed in a series of reports by Sniegocki and Reed (1963); Sniegocki and others (1963, 1965); and Sniegocki (1963a, 1963b, 1964). Reports by Price (1961) and by Price and others (1965) also discuss water chemistry in relation to artificial recharge and deal specifically with basalt hydrology.

Some physical, chemical, and bacteriological properties of water that may affect significantly an artificial-recharge program are: (1) suspended sediment, (2) entrapped gasses, (3) chemical precipitation, (4) temperature, and (5) bacteria and algae. The probable significance of these properties in artificial recharge practices are discussed in the foregoing references. They may or may not have an effect on artificial recharge in the Snake Plain aquifer, but they do warrant consideration.

Although a careful and comprehensive analysis of the effect of chemical reactions between dissolved constituents in the surface water to be used for artificial recharge and the native waters in the Snake Plain aquifer itself was beyond the scope of this report, no serious problems are foreseen. It seems that the recharge water most likely would be compatible with the ground water in both irrigated and nonirrigated parts of the Plain. (See fig. 10.) Even though some of the ground water in irrigated parts of the area contains more sodium, sulfate, and chloride ions than the surface waters, a mixing of the two probably would not cause significant chemical precipitation.

The approximate range in ground-water temperatures is from 10° to 16° Celsius (50° to 60° Fahrenheit). Depending on the time of application, the recharge water at the land surface may be as much as 15° Celsius (27° Fahrenheit) cooler than the ground water. This temperature difference could effect a resistance to mixing and thus cause density layering of water in the aquifer, wherein the cold recharged water would tend to seek the lower levels. The cold water also would be more viscous and thus slow down the process of recharge.

Monitoring of the suspended-sediment content of the recharge water is advisable. Ideally, water used for artificial recharge, especially for injection through wells, should be free of suspended sediment. Although the openings in the basalt aquifer may be large enough to carry sediment away from the recharge sites, accumulations of sediment eventually could reduce the ability of the aquifer to accept recharge, as previously stated. For example, a suspended-sediment load of 80 mg/l, the maximum observed concentration for Henrys Fork at St. Anthony (p. 25), amounts to about 11,000 tons per 100,000 acre-feet of water. At places where the danger of clogging by sediment is great, the problem can be minimized or eliminated by putting sediment traps in the conduit between the sources of recharge water and the sites of injection.

The following are conclusions reached regarding the chemical quality of this water:

1. The chemical quality of surface and ground waters in the Snake River Plain is suitable to most purposes for which they now are used.

2. There probably will be no chemical-quality problems involved in large-scale recharge.

3. Artificial recharge could improve the chemical quality in some areas by diluting the dissolved-solids content of the ground water.

4. If artificial recharge becomes a reality, a monitoring program should be established to determine the long-range effects on the hydrologic system.

EFFECTS OF ARTIFICIAL RECHARGE ON WATER LEVELS AND SPRING FLOW

The benefits to be derived from an artificial-recharge program are dependent on the volume of water added to storage in the aquifer, the subsequent build up in ground-water levels, and the length of time the recharge water remains in storage in a particular area. Assuming that all recharge water goes into storage in the aquifer, the volume of water added would equal the rate of recharge times the duration of the recharge period. However, the resultant effects on water levels and the length of time that the water would remain in storage are difficult to calculate. Predictions of the latter two factors are necessary to determine the economic feasibility and desirability of an artificial-recharge program.

Methods Available for Analysis

The response of an aquifer to man made stimuli, such as pumping or artificial recharge, is governed by its coefficient of storage and permeability, and by internal and peripheral hydraulic boundaries. Mathematical methods of analysis have been devised to enable prediction of some of the effects on ground-water flow caused by man's activity (Ferris and others, 1962). Application of those methods discussed by Ferris requires idealization of aquifer properties, including the necessity of regarding the aquifer as homogeneous and isotropic. Where the permeability varies from place to place, the aquifer is nonhomogeneous, and inasmuch as no aquifer is of infinite extent, boundary conditions exist which must be described. Mathematical solutions by ordinary methods under nonideal conditions are tedious, time consuming, and, for all but the simplest determinations of total aquifer response, impractical to attempt.

An alternative tool available to the hydrologist for the analysis of aquifers is the electric-analog model. The theory, instrumentation, and use of analog models for analysis of ground-water flow systems are described in many reports, among which are those by Skibitzke (1960), Patten (1965) and an earlier, unpublished manuscript, written by H. E. Skibitzke and G. M. Robinson in 1954, entitled "The use of numerical and electrical methods in solution of ground-water flow problems." The theory of analog modeling is based on an analogy between the flow of electricity and the flow of ground water. The analogous elements in the two systems are as follows:

Electric system	Ground-water system
Conductance--reciprocal of resistance (ohms)	Transmissibility (gallons per day per foot)
Capacitance (farads)	Storage coefficient (percent)
Voltage (volts)	Head (feet)
Current (amperes)	Volume rate of flow (acre-feet per year)
Time (micro-seconds)	Time (days)

These analogous elements are scaled to be directly proportional to one another and the physical limits of the electrical system are modeled proportionally to the physical limits of the aquifer. When the analogy is completed, almost any stress combination (including pumping and recharging) may be programmed into the model. The resultant responses, such as changes in water levels or discharge, are read throughout the entire model.

Some of the advantages of an analog model as a hydrologic tool are as follows:

1. An electric analog model can be used to analyze a complex nonhomogeneous ground-water system.

2. The model can integrate large amounts of geologic and hydrologic data into one system. Responses to either changing or continuous stresses such as pumping or recharge, can be measured and recorded at selected places throughout the entire system.

3. Because time in the model is in micro-seconds, predictive responses that represent many years into the future or past can be recorded in less than 1 second in the model.

4. When used as an experimental tool, resistors and capacitors representing values of transmissibility and storage, can be readily changed.

5. The model aids in pointing out places where field data are deficient or where further refinement of collected data is needed.

6. The model is readily adaptable to revisions or changes that may need to be made as additional data are obtained.

7. Initial construction can be done in a relatively short time and at a relatively low cost.

An electric-analog model was made of the Snake Plain aquifer so that the effects on ground-water levels and spring flows caused by recharging the aquifer at selected sites could be determined.

An early, somewhat simplified, electric-analog model of the Snake Plain aquifer was made for an idealized analysis of the flow system by Skibitzke and da Costa (1962). The simplified model was suited to the purposes of that study but would not have been sophisticated enough to suit the purposes of this study. As stated by the authors of that report (p. 49), "If all the data available today (1962) had been used, a much more detailed model and analysis could have been made."

Physical Conditions Affecting Ground-Water Flow

The Snake Plain aquifer comprises a series of basaltic lava flows which include interflow beds composed of pyroclastic and sedimentary materials. Ground-water movement is largely in and related to interflow zones, where permeable openings may range in size from cavernous lava tubes to capillary openings in sedimentary interbeds. Massive basalt, which makes up the central part of each individual lava flow, has few if any interconnected pore spaces and, therefore, is practically impermeable. The interflow zones are not completely separated one from another, but are interconnected along vertical rock joints or along fault zones, and at places where individual flows terminate. Also, feeder dikes for the lava may extend up through large thicknesses of basalt, and may extend laterally for miles. Individual dikes may terminate permeability channels in the flow rocks, or they may create additional permeability channels as a result of structural breakage attendant to their emplacement. Thus the ground-water flow system is anisotropic and nonhomogeneous, in contrast to an ideal sand and gravel aquifer where the flow system can be considered isotropic and homogeneous (permeability constant in all directions).

Anisotropy should result in disproportionate water-level responses within the aquifer when external stresses, such as changes in recharge and discharge, are applied. The disproportionate responses will tend to be maximum in local parts of the aquifer over relatively short periods of time. However, if the aquifer is viewed over many square miles, over long periods of time, the effects of the anisotropy should tend to a minimum; and, for all practical purposes, the aquifer should respond like an isotropic system. Therefore, in constructing an analog model of the entire aquifer, as was done for this study, a condition of isotropy was assumed.

The effects caused by nonhomogeneity (p. 33) are difficult to evaluate, but simplification of analysis can be accomplished by assuming the aquifer to be uniform in thickness, which largely may be the case. Hence, changes in transmissibility reflect only changes in permeability. (See Skibitzke and da Costa, 1962, p. 56.) Thus, the analog model, programmed with transmissibility values (fig. 12), can account for the nonhomogeneity of the aquifer.

The ratio of storage coefficient, S, to the transmissibility, T, expresses the diffusivity of the aquifer, that is, the rate at which the effects of either pumping or recharging will spread about the center of a stimulus. The storage coefficient is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. The transmissibility coefficient may be defined as the number of gallons of water, at the prevailing temperature, that will pass in 1 day through a 1-foot wide vertical strip of an aquifer, extending the saturated thickness of the aquifer, under a hydraulic gradient of 1 foot per foot. The smaller the ratio, S/T, the more rapid the spread of effects; and, conversely, the larger the ratio, the slower the spread. The transmissibility values used in this study are shown in figure 12. They were computed from the flow net drawn by Mundorff and others (1964, pl. 4), which is reintroduced in this report as figure 13.

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE STATE
OF IDAHO DEPARTMENT OF RECLAMATION

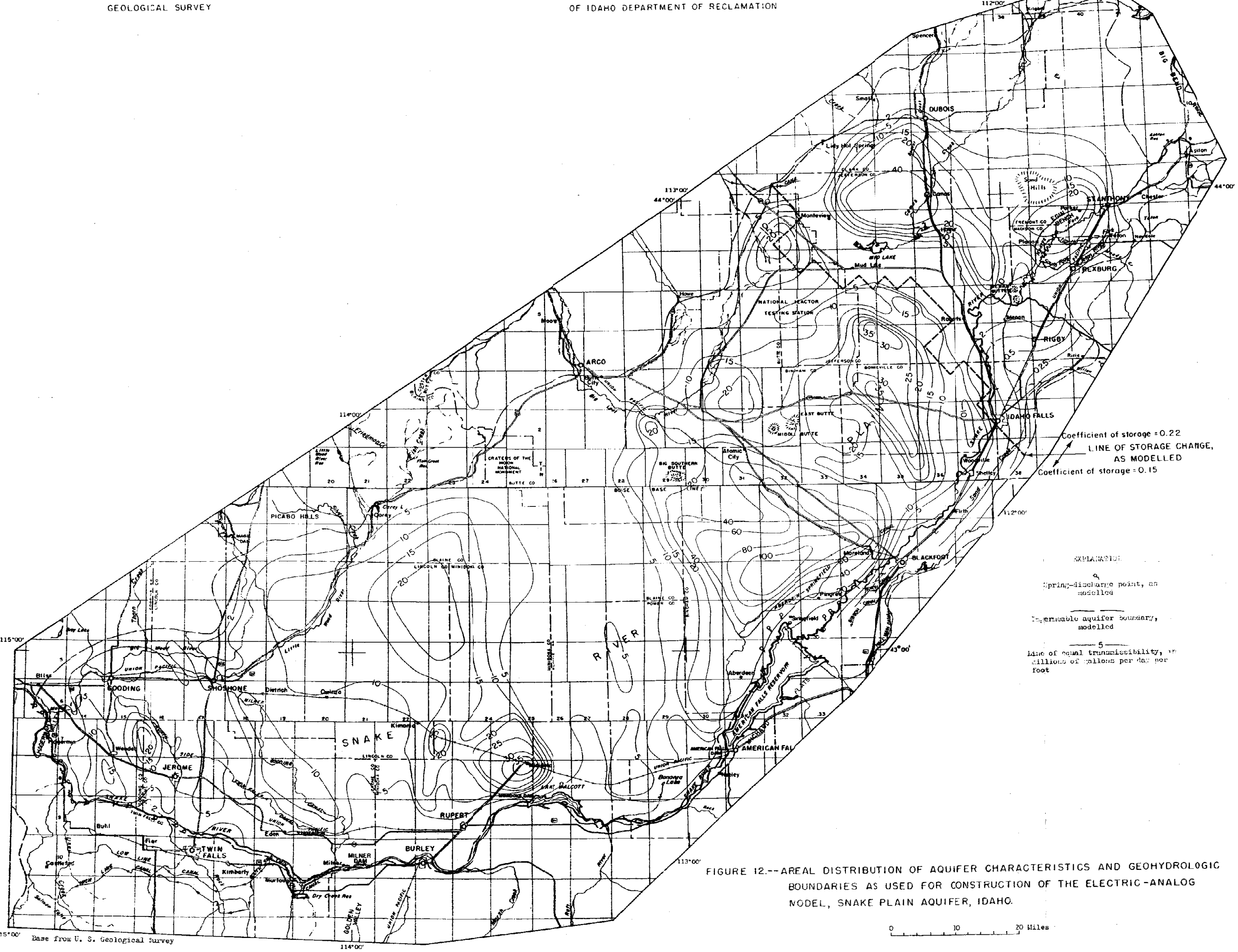

FIGURE 12.--AREAL DISTRIBUTION OF AQUIFER CHARACTERISTICS AND GEOHYDROLOGIC BOUNDARIES AS USED FOR CONSTRUCTION OF THE ELECTRIC-ANALOG MODEL, SNAKE PLAIN AQUIFER, IDAHO.

(A practical application of flow-net analysis is given by Bennett and Meyer, 1952.) Originally, all the T values derived from the flow net were used in the analog model, but upon testing, too much simulated water-level buildup occurred in the northeastern part of the aquifer (model). Therefore, in order to more closely match historical data, T values in a strip of the aquifer between Roberts and Monteview were increased. Because a perched water body is suspected to exist in the Mud Lake region, it was reasoned that possible error may have been introduced in the original flow net for that part of the aquifer. Furthermore, it was reasoned that the regional water table in that part of the aquifer south of Mud Lake may extend beneath the suspected perched water body and merge with the water table in the upper Mud Lake-Henrys Fork region, thus giving rise to assumption 11 on page 43. The truth of that assumption is contingent upon additional hydrologic field study. The need for additional study was exemplified by a well (NE¼ NW¼ sec. 2, T. 5 N., R. 36 E.) drilled by the U. S. Bureau of Reclamation in 1968 in the vicinity between the two parts of the aquifer referred to above. The well was drilled to a depth of 995 feet and penetrated basalt, cinders, and sediments, finally ending in clay at 990-995 feet. Three differing hydraulic pressure heads were obtained from different depths in the well. The pressure head in the depth interval between about 410 to 850 feet was above land surface. Thus, the aquifer interconnection in this part of the Plain is known to be very complex.

The values of the storage coefficient of the aquifer, shown on figure 12, were selected on the basis of results from pumping tests, laboratory determinations of porosity of basalts of the Snake River group, and results obtained from verifying the model. The values of S obtained during most of the pumping tests made in the aquifer were indicative of water-table conditions. (See

Ferris and others, 1962, p. 74-78.) However, some tests showed that artesian conditions also exist in places. Data were not available for describing an areal distribution of values for S as was done for values of T. For this reason it was necessary to use average values covering extremely wide areas of the aquifer. As shown by the diffusivity ratio, the values of S will have a decided effect upon what the water-level responses will be in different parts of the aquifer, at different periods of time.

Because the aquifer is largely a water-table aquifer, the value of S is essentially equal to the specific yield, that is, the volume of water involved in the gravity drainage or refilling of the aquifer, divided by the volume of the zone through which the water table moves. Thus the S value also has an effect on the magnitude of response due to recharge. Therefore, when recharged with equal volumes of water, a part of the aquifer having a large S value will show a lesser water-level rise than a part having a smaller S value.

In addition to the inhomogeneities within the main aquifer, the situation is complicated further by perched or semiperched water bodies which overlie the main aquifer. Probable perched-water bodies of poorly defined areal and vertical extent occur in the vicinities of Mud and Market Lakes, as inferred previously, Egin Bench, American Falls Reservoir, and in the Rupert-Burley and Bonanza Lake areas. The downward rate of percolation from the perched or semiperched water bodies to the main aquifer is unknown. The same factors are unknown where the Snake River is perched above the main aquifer. If the hydraulic characteristics of the perched-water bodies and their hydraulic connection with the main aquifer were known, it would be possible to build a multi-layered model showing vertical flow between the different aquifer units. However, because of the above unknowns, it was necessary to make the assumptions listed as 8 and 10 in the following section of this report. Also, the interconnection between flow zones within the main aquifer that are separated by massive rock layers in the vertical direction are unknown, and assumption 3 necessarily was formulated.

Hydrologic boundaries are an important factor in the analysis of any system of flow. The delineation and significance of the hydrologic boundaries of the Snake Plain aquifer are described in some detail by Mundorff and others (1964, p. 193-194), and their mapping of the boundaries is shown in figure 13 of this study. As stated in that report, the real boundaries are approximated as straight-line segments most suitable for the analysis desired. In this study, where an electric-analog model was made, adherence to the real shape of the boundaries adds no hardship to the analyses. Therefore, the peripheral boundaries of the aquifer, as shown in figure 12, conform more closely to the actual extent of the aquifer than do those boundaries shown on figure 13. Where the aquifer terminates at its contact with rocks in the surrounding uplands, the boundaries are mapped as negative or impermeable as defined by Mundorff. That is, when pumping or recharging the main aquifer, no additional drawdown or build-up of water levels will occur beyond those boundaries; and any responses within the main aquifer will be reflected, hence, intensified, at those boundaries. Where the water flows out of springs in the Blackfoot-American Falls and Milner-King Hill areas, the boundaries are mapped as positive or discharge boundaries. That is, when pumping or recharging the main aquifer, the flow at the positive boundaries will be altered such that no additional drawdown or build up of water levels will occur within the main aquifer at those boundaries. For the purpose of this study, the Snake River conveniently was taken as the southern boundary of the aquifer. The extent of the aquifer on the south side of the river is somewhat nebulous and its inclusion would add little, if any, to the final results of this study. The stretch of the river between the center of American Falls Reservoir and Milner Dam, that is shown as a positive boundary on figure 13, was mapped as an impermeable boundary for this study. Flow from the springs along parts of that stretch is minor (p. 20) and the interrelation between spring flow, the perched-water bodies, and the Snake Plain aquifer is not known in that area. Also, the boundaries shown on figure 13 to lie within the limits of the aquifer in the northeast part of the Plain are excluded from the analog model made for this work, largely because the hydraulic connection between the perched-water bodies and the main aquifer is not known.

It is virtually impossible to describe in detail the complexities of the hydrologic system underlying the Snake River Plain. Enough data were available, however, to build a workable analog model of the Snake Plain aquifer. This model can predict water-level responses to artificial recharge or ground-water withdrawal which are generalized in areal extent and are within a reasonable range of accuracy. However, for lack of better definition of the hydrology of the aquifer, deviations from the model predictions must be expected.

Analog Model Construction and Use

The analysis of the hydrologic system of the Snake Plain aquifer and the construction and use of the electric-analog model are based on the following assumptions and conditions:

1. The aquifer is essentially a water-table (unconfined) aquifer.
2. The aquifer reacts regionally as a nonhomogeneous and isotropic system.
3. Ground-water flow within the aquifer is laminar (as opposed to turbulent) and two dimensional.

4. The aquifer is of uniform thickness.

5. Coefficients of transmissibility (fig. 12) derived from the flow-net analysis represent the entire thickness of the aquifer and do not change with time.

6. The storage coefficient of the aquifer averages 0.15 and 0.22 within the areas shown in figure 12.

7. The only significant natural discharge from the aquifer occurs as springflow between the mouth of the Blackfoot River and American Falls Reservoir and between Twin Falls and Bliss.

8. The Snake River recharges the aquifer in those stretches along which springs do not occur, but the percolation to the regional water table occurs as unsaturated flow.

9. The volume difference between gross pumpage and consumptively used pumpage in the ground-water irrigated areas returns as recharge to the aquifer at the same time as pumping occurs.

10. Recharge to the perched-water bodies as a result of surface-water irrigation is transmitted to the main aquifer as an equal volume of recharge during a single irrigation season.

11. The regional water table in the main aquifer is below a perched water table in the Mud Lake area and the two gradually merge north of Mud Lake.

12. Artificial recharge has zero transit time while moving from the recharge point, through the unsaturated zone, to the water table. Thus any simulation of artificial recharge in the model represents a direct addition of water into the main aquifer.

13. Natural recharge to and discharge from the aquifer remain constant tin time and thus can be eliminated from the analysis of the system. (See Skibitzke, 1960.)

The model consists of a grid network of resistors that are inversely proportional to transmissibility, and of capacitors whose values are directly proportional to the storage coefficient. Except at those places where springs occur, all aquifer boundaries are modeled as negative (impermeable) boundaries. The western springs are modeled as a discharge boundary. The electrical components are grounded directly along this boundary and current (water) is allowed to flow freely out of the model. Originally, the eastern springs were modeled likewise, but, upon testing, too much current flowed out of the model. Therefore, in order to match the actual spring flow more reasonably, additional resistors were added between the network and the ground. Current flow from the eastern springs in the model was restricted to an upper limit through the use of the resistors.

The current (water) flow at the springs, the potential (water level) changes within the model, and the addition or reduction of current (water) stored in the capacitors caused by the addition or withdrawal of current anywhere on the network, are measured by electrical apparatus and recorded through use of an oscilloscope. The oscilloscope readings then can be translated to their analogous values (spring discharge and water levels) in the hydraulic system.

Validation of Model

To determine if the analog model would respond in the same manner as the Snake Plain aquifer to programmed artificial-recharge activities, an attempt was made to verify the model. This was done by using historical data that related changes in ground-water levels and spring flow to known events such as changes in recharge to and discharge from the aquifer resulting from irrigation. In accord with assumption 13, no natural recharge or discharge was considered in the validation.

Prior to irrigation, the hydrologic system of the Snake River Plain was in a state of equilibrium. That is, long-term average recharge to the aquifer equalled discharge and ground-water levels everywhere in the aquifer were effectively constant. However, with the advent of irrigation by surface water in the late 1800's and early 1900's, recharge to the aquifer increased. As a result, ground-water levels rose, and discharge from the springs between Milner and King Hill increased (fig. 8), indicating that the aquifer was in a state of nonequilibrium. From about the late 1940's until the mid-1950's, discharge from the springs was again stable, indicating that new equilibrium conditions were attained. However, beginning in about 1954, the increasing use of ground water for irrigation lowered water levels in the aquifer. (See fig. 4.) As a result, spring discharge began to decline and nonequilibrium conditions again prevailed. Historical data describing the changes in recharge due to surface-water irrigation, and in discharge resulting from increased ground-water use, were programmed into the analog model.

Comparison of the water-level changes produced in the model with the water-level changes actually observed in the aquifer provided a basis for determining the validity of the model. Although complete verification of the model was not obtained, reasonable comparisons between actual and model-produced water-level changes were derived for that part of the aquifer westward from Lake Walcott. Eastward from Lake Walcott, where historical water-level data and data descriptive of the hydrology of the aquifer are grossly lacking, verification has not yet been attained.

Using the Model

The following hypothetical-recharge program was set up to test the versatility of the model and its practical use. Four areas on the Plain were selected as places for recharge (fig. 14). The sites are located up gradient from areas of present or future development of ground-water irrigation and distant from areas of natural discharge from the aquifer. Also, they are places where it may be possible to convey water by gravity flow. It is postulated in the program below that artificial recharge can be applied to the aquifer at these places. No inference is intended here as to the most practical rate or means of artificial recharge used at each particular place. Such determinations will require further field studies.

Recharge was simulated simultaneously in each of the four areas at a rate of about 62,000 acre-feet of water per month for 3 consecutive months; then, no water was added for 21 months. This cycle was repeated for four more like periods. This amounted to a total recharge of about 740,000 acre-feet for each biennium or a grand total of 3.7 million acre-feet in the 10-year test period. Water-level rises were recorded at the end of the fifth biennium. Rises in water levels resulting from the hypothetical recharge program are contoured in figure 14. Also shown on figure 14 are water-level hydrographs at different places in the aquifer, throughout the entire 10-year recharge program, and the cumulative increases in spring flows resulting from the artificial recharge.

As a result of the above conditions of hypothetical recharge, water-level rises ranging from less than 1 to more than 5 feet are indicated for the aquifer. The rise of more than 5 feet occurs close to the area of greatest combined recharge northeast of Blackfoot near an impermeable boundary and in a zone of low transmissibility. The water-level rises at the end of the 10 years, as shown by the contours, do not center around the recharge areas because the contours are drawn on readings taken 21 months after completion of the last recharge cycle; and, therefore, the recharged water has had time to migrate. The expected periodic peaks and declines of the ground-water mounds

GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE STATE OF IDAHO DEPARTMENT OF RECLAMATION

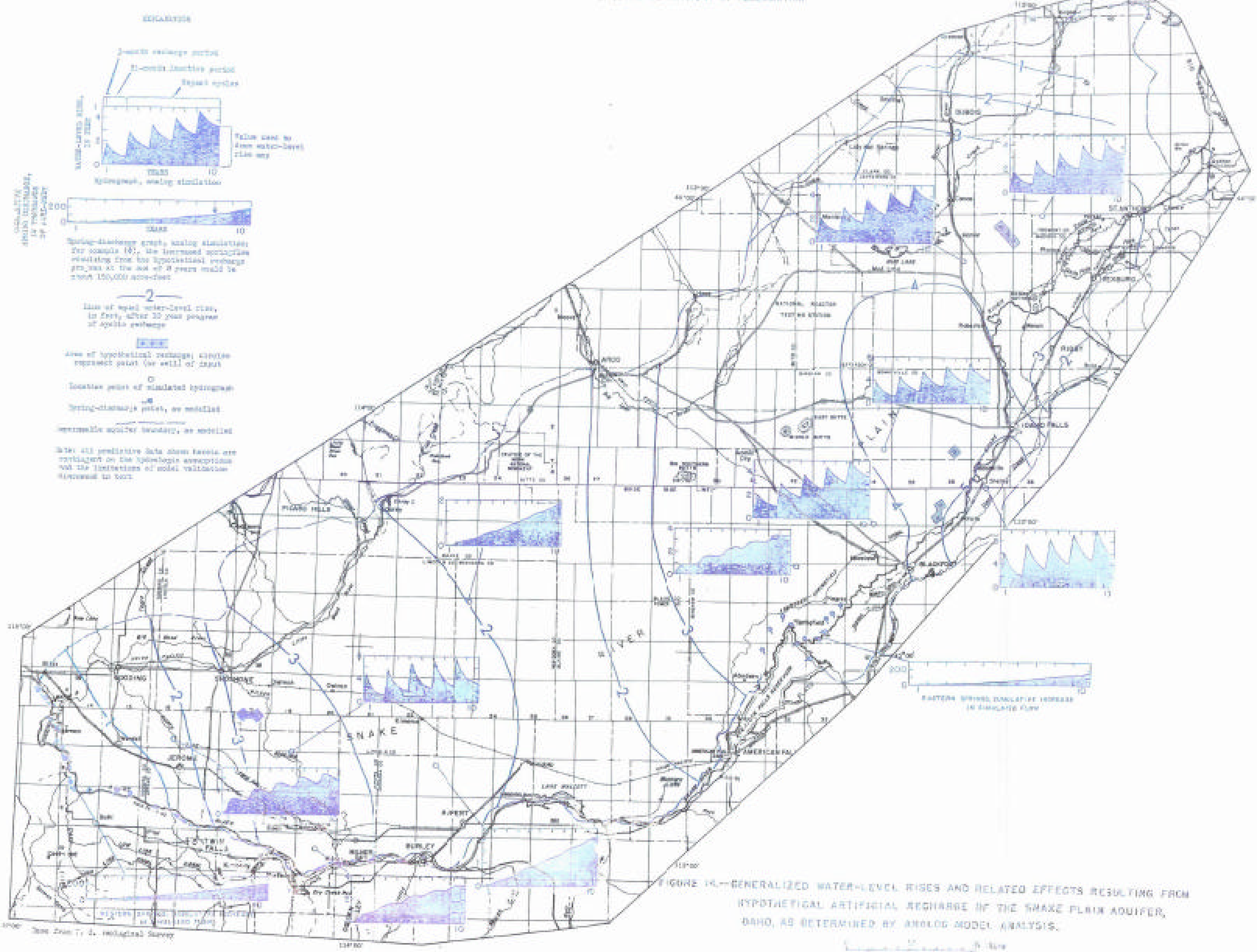

FIGURE 14.—GENERALIZED WATER-LEVEL RISES AND RELATED EFFECTS RESULTING FROM HYPOTHETICAL ARTIFICIAL RECHARGE OF THE SNAKE PLAIN AQUIFER, IDAHO, AS DETERMINED BY ANALOG MODEL ANALYSIS.

are evident on the water-level hydrographs. The rate of rise, magnitude, and dissipation of the mounds, at selected places, can be obtained from the hydrographs. For example, at the hydrograph site 1½ miles southeast of Shelley (fig. 14), the simulated water-level rise was about 4.4 feet during the initial 3-month recharge period, or the water level rose at a rate of about 1.1 feet per month. At the end of 5 months, 2 months after cessation of recharge, the water-level rise peaked at about 5.8 feet. At the end of 1 year, the water level receded 2.3 feet to a residual rise of 3.5 feet. At the end of 2 years, the water level dropped an additional 1.5 feet to a residual rise of 2 feet. The same calculations can be made for the remaining four periods of hypothetical recharge. Thus, the model can be used to evaluate the effects of recharge in any direction or at any distance from an area of recharge, through use of the hydrographs. Magnitudes of water-level rise taken from the hydrographs were measured to the nearest tenth of a foot for this example only. It must be remembered that the analog readouts are approximations and cannot simulate water-level rises that may occur in the aquifer to that degree of accuracy.

The analog-model readouts indicated that if 3.7 million acre-feet of water were artificially recharged in the manner described, about 3.3 million acre-feet (88 percent) would go into storage in the aquifer and about 0.4 million acre-feet (12 percent) would be added to the flow out of the springs.

The model has no built-in water-table gradient and the resultant rises in water levels and the increases in spring flow presented are wholly due to the effects of the artificial recharge as programmed. However, in actual practice, there will be a water-table gradient that would have some unknown effect upon the shape and the dispersion of the recharge responses. Also, in actual practice, the water-level changes due to artificial recharge would be superimposed on existing man made and natural hydrologic stresses. Because the annual increments of the artificially induced rise are small, they probably would not be noticeable among the seasonal fluctuations of water levels, except, perhaps, in areas close to recharge sites.

Deficiencies of Data and Need for Future Studies

The greatest determinant of accuracy in the responses obtained using the analog model is the reliability of the data used to describe the hydrologic system. At the very outset of this work it was recognized that only approximate descriptions of the pertinent elements in the system were obtainable. The following are some of the weaknesses and deficiencies in data that suggest needs for further study:

1. The hydraulic relations between the regional water table and the perched-table bodies (p. 40) are unknown, and their areal and vertical extents have not been mapped.

2. A true distribution of values for the coefficient of storage throughout the aquifer is not available and may be unobtainable. Considering that the coefficient of storage for a cavernous lava tube may be 100 percent, very high in vesicular cindery interbeds, and practically nil in massive basalt, it is difficult to estimate actual storage coefficients for the entire aquifer.

3. The thickness of the aquifer is unknown.

4. The flow net used to estimate coefficients of transmissibility lacks control for definition of water-table contours around the outer edges and in the west-north-central and extreme northeastern parts of the aquifer. Therefore the transmissibility values are difficult to estimate in those places. Also the spatial distribution and number of flow lines in the net necessarily were based largely on gross estimates of recharge.

5. The actual diffusion of pressure responses through the aquifer is unknown. It has been suggested that massive recharge creates pressure waves that cause water-level rises throughout the aquifer faster than would be expected under water-table conditions. (Barraclough and others, 1965, p. 67.) Only responses that are governed by water-table conditions will occur in the model made for this study.

6. A comprehensive pre-irrigation water-table map for use in validating the model is unavailable.

7. Pre-irrigation spring-flow records are unavailable.

8. More firm values for recharge to the aquifer from ground- and surface-water irrigation are needed to replace the estimates made in this study.

9. Data are not available to estimate and distribute total recharge to the aquifer from natural sources on an annual basis.

10. The electric-analog response is based on the assumption of an isotropic aquifer. But field data indicate that for conditions where recharge or discharge are applied to the upper boundary (water table), the aquifer will be anisotropic. Transmissibilities obtained from flow-net analysis (p. 39) may not be realized in the vicinity of recharge owing to the relatively low vertical permeability of stratified flows. Therefore, the model shows water-level changes that are the minimum that actually would occur in the field in the vicinity of points of artificial recharge, unless the recharge was applied in a well that penetrated the entire saturated thickness of the aquifer.

Considering the great extent and the complex nature of the Snake Plain aquifer, the responses obtained from the analog model are believed to be reasonable despite the assumptions and the deficiencies in data.

Items 6 and 7 above emphasize the lack of historical data which are needed for full validation of any model, but which are unobtainable. Items 1 and 4 above indicate elements needed for refinement of the model but which probably are obtainable. The usefulness of the model would be enhanced considerably if the elements of items 1 and 4 were described in greater detail. These descriptions will require test drilling in areas of perched-water bodies in order to delineate their areal and vertical extents and to test their hydraulic properties. The test holes also would enable differentiation of the perched-water tables and the regional water table in the model. Additional test holes are needed in remote parts of the Plain where the altitude of the regional water table is unknown. Acquisition of those water-table data would enable the drawing of a more detailed water-table map of the Snake Plain aquifer. Re-evaluation of the areal distribution of recharge to the aquifer coupled with a more detailed water-table map would enable the drawing of a more refined flow net. The refined flow net, in turn, would enable the derivation of more accurate coefficients of transmissibility to be distributed throughout the aquifer and to be used to refine the present analog model.

Items 2 and 5 above are prime elements for study that can benefit from additional research. These two elements might best be studied separately from the overall appraisal of artificial recharge to the Snake Plain aquifer so that research aspects can be stressed. The results obtained then can be used in the overall appraisal.

It should be recognized that a precise model of the Snake Plain aquifer can never be built. Predictions of future water-level changes obtained from any model always will be subject to some range of probability and will require some degree of interpretation. This is because of the complexities of the hydrologic system, including the huge size and the great variability of the aquifer, and the variations in recharge, storage, movement, and discharge of ground water through the aquifer. However, in its present state of development, the Snake Plain analog model is a useful hydrologic tool. Without a model, water managers would be required to use largely qualitative methods to estimate the effect of artificial recharge on water levels. Although it was not possible to fully validate the present model, the model is the best scientific tool available at this time.

What may be considered the first phase of study, this and Mundorff's (1962) studies, has shown that artificial recharge of the Snake Plain aquifer is probably feasible. This study, in particular, gives the frequency of occurrence and volumes of surplus water that may be available. It also points out the general magnitude of water-level rises that may be expected if a given amount of water is recharged. Mundorff's study (1962) discussed a number of places on the Plain where water might be recharged either by water spreading or through recharge wells.

The analog model, in its present stage of development, is a valuable aid for use in what could be called a second phase of study preparatory to actual artificial recharge of the Snake Plain aquifer. As a part of the second phase of study, proposed recharge sites could be selected and examined in some detail, geologically and hydrologically, before they are used. Also the means of conveyance of surplus water to the selected recharge sites must be studied. The model can be used to approximate the effects upon the water-table caused by deep percolation losses along the conveyance system and by recharge at each individual site, under any pattern of suggested operation.

If water spreading is to be the means of artificial recharge, it will be necessary to work out the subsurface geology at each recharge site. Undoubtedly, there are places on the Plain where the surfacial lava has a great enough infiltration capacity to accept the large volumes of water that may be available for recharge. However, if an impermeable bed or layer of low permeability occurs in the subsurface above the regional water table, there is a distinct possibility that the recharge water could move laterally towards low-altitude farm lands around the edges of, and within, the elevated lava fields. If this condition was not recognized, water logging or even flooding of farm lands could occur. An injection well is probably the only positive means of assurance that the recharge water will go directly into the main aquifer. At all potential recharge sites, drilling of test holes to penetrate the regional water table is the best means by which to study the subsurface geology and determine the local hydrology. These holes could be converted to recharge wells.

Any additional hydrologic data gained during a second phase of study could be used to refine the present analog model. Also, any data gained in future individual areas studied on the Plain may be used in the model; and conversely, the model may be used as a guide to select areas for future studies.

A third phase in the artificial-recharge studies then would be to conceive a recharge program, put it into actual operation, and monitor the effects.

SUMMARY AND CONCLUSIONS

1. By the end of the 1965 irrigation season, an estimated 1,510,000 acres was irrigated within the area of this study--910,000 acres by surface-water diversions and 600,000 acres by ground-water pumping. An estimated 6 percent (52,000 acres) of the area irrigated by surface-water diversions is supplementally irrigated with ground water pumped from wells.

2. During the decade 1956-65, an estimated average total annual diversion of 6.6 million acre-feet of surface water was distributed to the heads

of the main irrigation canals. Of this total, about 4 million acre-feet of water or 60 percent seeped into the ground and recharged the Snake Plain aquifer.

3. In 1965, an estimated 2.1 million acre-feet of water was pumped from wells for irrigation. Of this total, about 1.1 million acre-feet or 52 percent of the pumped water seeped back into the ground to recharge the Snake Plain aquifer.

4. The major sources of water for artificial recharge to the Snake Plain aquifer are the Snake River upstream from Milner Dam, and Henrys Fork. The key point in the system is Milner Dam; any excess streamflow past this point might have been diverted upstream for artificial recharge. On the basis of a recurrence interval determination of annual mean discharge of Snake River at Milner, an annual mean discharge of about 1.3 million acre-feet or more occurs, on the average, once every 2 years. This indicates a 50 percent statistical probability that the same discharge may be equalled or exceeded in any 1 year. Actual flow patterns are controlled largely by reservoir storages and releases and do not closely follow the statistical patterns.

5. Natural ground-water discharge from the Snake Plain aquifer occurs almost wholly from two groups of springs along the Snake River. The easternmost group of springs accounts for about 1.8 million acre-feet per year (1954-65 average). The westernmost group accounts for about 4.7 million acre-feet per year.

6. The chemical quality of surface and ground water in the Snake River Plain is suitable for most uses. There probably will be no chemical-quality problems involved in large-scale artificial recharge. Artificial recharge could improve the chemical quality of water in some areas by lowering the dissolved-solids concentration of the ground water.

7. If artificial recharge becomes a reality, a monitoring program should be established to measure the long-range effects on the hydrologic system.

8. The electric analog model of the Snake Plain aquifer can be expected to approximate regional water-level responses to artificial recharge or ground-water withdrawal with a reasonable degree of accuracy. However, because of the complexities in the natural system and the lack of hydrologic data for the aquifer, deviations from the model predictions must be expected. The model predicts that by cyclicly adding 186,000 acre-feet of water during 3 continuous months at each of four different places on the Plain, biannually for five bi-ennial periods, water levels would rise from less than 1 to more than 5 feet in the aquifer. This amounts to a total of 3.7 million acre-feet during the period of recharge--3.3 million acre-feet would go into storage in the aquifer and 0.4 million acre-feet would flow out of the springs. These effects, with some reservations, would be superimposed upon the existing man made and natural hydrologic stresses. Because the annual increments of change would be small, they probably would not be noticeable among the seasonal fluctuations of water levels and spring flows, except perhaps in those areas that are close to the recharge sites.

9. A completely satisfactory validation of the analog model was not accomplished. Additional acquisition of field data by means of test drilling and re-evaluation of the areal distribution of recharge to the aquifer are needed to refine the present model. After refinement, the usefulness of the model would be enhanced considerably.

REFERENCES

Barraclough, J. T., Teasdale, W. E., and Jensen, R. G., 1967, Hydrology of the National Reactor Testing Station, Idaho, annual progress report, 1965: U. S. Geol. Survey open-file rept., 107 p.

Bennett, R. R., and Meyer, R. R., 1952, Geology and ground-water resources of the Baltimore area: Maryland Dept. Geology, Mines and Water Resources Bull. 4, 573 p.

Ferris, J. G., Knowles, D. B., Brown, R. H., and Stallman, R. W., 1962, Theory of aquifer tests: U. S. Geol. Survey Water-Supply Paper 1536-E, 174 p.

Fishel, V. C., 1942, Discharging apparatus in Wenzel, L. K., Methods for determining permeability of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 887, p. 56-65.

Hem, J. D., 1959, Study and interpretation of the chemical characteristics of natural water: U. S. Geol. Survey Water-Supply Paper 1473, 269 p.

Hoyt, W. G., 1935, Water utilization in the Snake River Basin: U. S. Geol. Survey Water-Supply Paper 657, 379 p.

Jensen, M. C., and Criddle, W.D., 1952, Estimated irrigation requirements for Idaho: Idaho Univ. Agr. Expt. Sta. Bull. 291, 23 p.

Laird, L. B., 1964, Chemical quality of the surface waters of the Snake River Basin: U. S. Geol. Survey Prof. Paper 417-D, 47 p.

McConnell, J. B., 1967, Chemical quality investigations of surface water in Idaho, 1965-66: U. S. Geol. Survey open-file report, 25 p.

Mundorff, M. J., 1962, Feasibility of artificial recharge in the Snake River Basin, Idaho: U. S. Geol. Survey open-file rept., 49 p.

Mundorff, M. J., Crosthwaite, E. G., and Kilburn, Chabot, 1964, Ground water for irrigation in the Snake River Basin in Idaho: U. S. Geol. Survey Water-Supply Paper 1654, 224. p.

Patten, E. P., Jr., 1965, Design, construction, and use of electric analog models, in Wood, L. A., and Gabrysch, R. K., Analog model study of ground water in the Houston district, Texas: Texas Water Comm. Bull, 6508, p. 41-60.

Price, C. E., 1961, Artificial recharge through a well tapping basalt aquifer, Walla Walla area, Washington: U. S. Geol. Survey-Water Supply Paper 1594-A, 33 p.

Price, Don, Hart, D. H., and Foxworthy, B. L., 1965, Artificial recharge in Oregon and Washington, 1962: U. S. Geol. Survey-Water Supply Paper 1594-C, 65 p.

Rainwater, F. H., 1962, Stream composition of the conterminous United States: U. S. Geol. Survey Hydrol. Inv. Atlas, HA-61, 3 pls.

Russell, I. C., 1902, Geology and water resources of the Snake River Plains of Idaho: U. S. Geol. Survey Bull. 199, 192 p.

Simons, W. D., 1953, Irrigation and streamflow depletion in Columbia River Basin above The Dalles, Oregon: U. S. Geological Survey Water-Supply Paper 1220, 126 p.

Skibitzke, H. E., 1960, Electronic computers as an aid to the analysis of hydrologic problems: 12th Gen. Assembly, Internat. Union of Geodesy Geophysics, Helsinki, Finland, July 25 - August 6, 1960.

Skibtizke, H. E., and da Costa, J. A., 1962, The ground-water flow system in the Snake River Plain, Idaho--an idealized analysis: U. S. Geolo. Survey Water-Supply Paper 1536-D, 67 p.

Sniegocki, R. T., 1963a, Geochemical aspects of artificial recharge in the Grand Prairie Region, Arkansas: U. S. Geol. Survey Water-Supply Paper 1615-E. 41 p.

REFERENCES (Cont'd.)

_____ 1963b, Problems in artificial recharge through wells in the Grand Prairie Region, Arkansas: U. S. Geol. Survey Water-Supply Paper 1615-F, 25 p.

_____ 1964, Hydrogeology of a part of the Grand Prairie Region, Arkansas: U. S. Geol. Survey Water-Supply Paper 1615-B, 72 p.

Sniegocki, R. T., Bayley 3d, F. H., and Engler, Kyle, 1963, Equipment and controls used in studies of artificial recharge in the Grand Prairie Region, Arkansas: U. S. Geol. Survey Water-Supply Paper 1615-C, 39 p.

Sniegocki, R. T., Bayley 3d, F. H., Engler, Kyle, and Stephens, J. W., 1965, Testing procedures and results of studies of artificial recharge in the Grand Prairie Region, Arkansas: U. S. Geol. Survey Water-Supply Paper 1615-G, 56 p.

Sniegocki, R. T., and Reed, J. E., 1963, Principles of siphons with respect to the artificial-recharge studies in the Grand Prairie Region, Arkansas: U. S. Geol. Survey Water-Supply Paper 1615-D, 19 p.

Stearns, H. T., Crandall, Lynn, and Steward, W. G., 1938, Geology and ground-water resources of the Snake River Plain in southeastern Idaho: U. S. Geol. Survey Water-Supply Paper 774, 268 p.